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Cognitive Vehicle Platooning in the Era of Automated Electric Transportation

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COGNITIVE VEHICLE PLATOONING IN THE ERA OF AUTOMATED ELECTRIC TRANSPORTATION

by

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Approved:

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Abstract

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Vehicle platooning is an important innovation in the automotive industry that aims at improving safety, mileage, efficiency, and the time needed to travel. This research focuses on the various aspects of vehicle platooning, one of the important aspects being analysis of different control strategies that lead to a stable and robust platoon. Safety of passengers being a very important consideration, the control design should be such that the controller remains robust under uncertain environments. As a part of the Department of Energy (DOE) project, this research also tries to show a demonstration of vehicle platooning using robots. In an automated highway scenario, a vehicle platoon can be thought of as a string of vehicles, following one another as a platoon. Being equipped by wireless communication capabilities, these vehicles communicate with one another to maintain their formation as a platoon, hence are "cognitive."

Autonomous capable vehicles in tightly spaced, computer-controlled platoons will lead to savings in energy due to reduced aerodynamic forces, as well as increased passenger comfort since there will be no sudden accelerations or decelerations. Impacts in the occurrence of collisions, if any, will be very low. The greatest benefit obtained is, however, an increase in highway capacity, along with reduction in traffic congestion, pollution, and energy consumption.

Another aspect of this project is the automated electric transportation (AET). This aims at providing energy directly to vehicles from electric highways, thus reducing their energy consumption and CO_2 emission. By eliminating the use of overhead wires, infrastructure can be upgraded by electrifying highways and providing energy on demand and in real time to moving vehicles via a wireless energy transfer phenomenon known as "wireless inductive coupling." The work done in this research will help to gain an insight into vehicle platooning and the control system related to maintaining the vehicles in this formation.

(120 pages)

Public Abstract

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This research focuses on a concept called "cognitive vehicle platooning." A group of vehicles, either of the same type or different, following one another at highway speeds, coupled together by wireless communication is vehicle platooning. With this technology, passengers can comfortably enjoy their rides without having to drive their cars, as the cars will drive themselves. This automatic car driving is an advanced form of cruise control. These cars will run on dedicated lanes on highways. The leader of the platoon communicates wirelessly to its followers, its position, velocity, and acceleration information. Using this data, the followers will have a control algorithm that computes the position, velocity, and acceleration information necessary for them to keep safe distances between each other, at the same time, follow the lead vehicle's speed. Each vehicle preceding the leader communicates wirelessly with the leader as well as the immediate preceding vehicle. This constitutes two control systems, "lateral control (steering)" and "longitudinal control (inter-vehicular spacing control)." Such a technology, if introduced on existing highways, will lead to passenger comfort, reduced fuel consumption, less time needed to travel, reduced traffic congestions, and increased highway capacity. In addition to this introduction of automatic control into vehicles, these vehicles will be electric vehicles and will be wirelessly charged by magnetic

pads buried under the roadways, while in motion. This concept is called “automated electric transportation.”

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Pooja Kavathekar

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Acronyms

DOE	Department of Energy
AET	Automated Electric Transportation
CSOIS	Center for Self-Organizing and Intelligent Systems
REU	Research Experience for Undergraduates
AHS	Automated Highway Systems
NAHSC	National Automated Highway System Consortium
MASNET	Mobile Actuator and Sensor Network
PATH	California Partners for Advanced Transit and Highways
CPS	Cyber-Physical Systems
WSN	Wireless Sensor Networks
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
IVC	Inter Vehicular Communications
SARTRE	Safe Road Trains for the Environment
CFD	Computational Fluid Dynamics
MAC	Media Access Control
DSRC	Dedicated Short Range Communications
WAVE	Wireless Access in Vehicular Environments
UCAV	Uninhabited Combat Air Vehicles
CCA	Cooperative Collision Avoidance
VANET	Vehicular Ad-hoc Networks
SSVS	Super Smart Vehicle Systems
COCAIN	Cooperative Optimized Channel Access for Inter-vehicle Communications
TELCO	Telecommunication Network for Cooperative Driving
DOLPHIN	Dedicated Omni-purpose Inter-vehicle Communication Protocol
ACC	Automatic Cruise Control
VHF	Very High Frequency

GPS	Global Positioning System
pGPS	Psuedo Global Positioning System
ISM	Industrial, Scientific, and Medical
RCS	Remote Control Station
TDMA	Time Division Multiple Access
CSMA	Carrier Sense Multiple Access
SS	Spread Spectrum
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
IrDA	Infrared Data Association
DS-CDMA	Direct Sequence CDMA
MC-CDMA	Multi-Carrier Code Division Multiple Access
AVCS	Automatic Vehicle Control System
RIBC	Robust Intelligent Back Stepping Control
CMAC	Cerebellar Model Articulation Controller
MFC	Microsoft Foundation Classes
ISE	Integral Square Error

Chapter 1

Introduction

1.1 Overview

The concept of vehicle platooning is relatively new. Vehicle platooning can be considered as an important innovation in the automotive industry that would have provide the following benefits:

- Increased highway capacity,
- Improved vehicle safety,
- Improved mileage due to reduced aerodynamic drag,
- Increased efficiency,
- Decreased traffic congestion,
- Reduced environmental pollution,
- Increased passenger comfort.

Automated vehicles resemble the migration of birds or a group of dolphins under cooperative driving; aerodynamic efficiency is the main reason for the formation of birds in the migration, and dolphins communicate with each other while swimming to avoid collisions. Cognitive platooning, which can be compared to these examples, will contribute to increase in road capacity as well as road traffic safety. The aerodynamically efficient formation of vehicles in a platoon will reduce aerodynamic drag, thus improving fuel economy. Vehicle platooning is illustrated in Fig. 1.1, as implemented by Robinson et al. [1] in the SARTRE Demo.

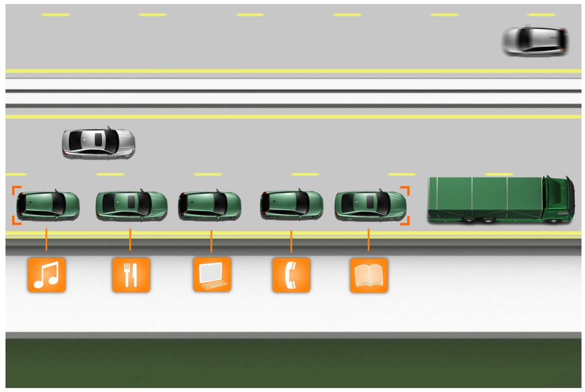

Fig. 1.1: Vehicle platooning as shown by the SARTRE demo.

1.2 Motivation: Why Cognitive and Why Platooning?

Automated highway systems (AHS) have been a well researched topic in literature. This concept is not exactly new. General Motors showed a working model as far back as in the 1939's World Fair. Most of this research has resulted in proof of technical feasibility put on by national automated highway system consortium (NAHSC) in San Diego in August 1997. As far back as 1970, prototype equipment was operationally tested. Actual research began in 1960, as can be seen in the paper by Hanson [2] and Shladover [3] has given a very extensive review of the AHS research done. A lot of advancement has taken place since then. The main cause of excessive energy consumption is the drag force experienced by a vehicle. This is highly and linearly dependent on the size and velocity of the vehicle. In 1995, a research report presented a detailed description on the aerodynamic performance of platoons, revealing that the drag coefficient experienced about 55% reduction on average in 2, 3, and 4 vehicle platoons leading to a reduction in fuel consumption. This report was submitted to the California partners for advanced transit and highways (PATH), as cited by Levedahl et al. [4].

With such benefits obtained with vehicle platooning, it is a well researched topic. Moreover, introduction of inter-vehicular communications between vehicles not only ensures individual vehicle stability, but also global platoon stability. Introducing this cognitive controller design will guarantee stability of the entire platoon.

At its inception, the goal of the research work was to to be able to utilize the mobile actuator and sensor network (MASnet) platform developed at CSOIS for a demonstration of vehicle platooning using the MASmotes. However, due to software and hardware limitations, the research platform was changed to a LEGO mindstorm NXT 2.0. Using this platform, different control strategies for vehicle platooning were demonstrated. This research focuses on analysis of controller design for stability under uncertain environments as well as robustness to model uncertainties, parameter uncertainties, noise in measurement signals, and model errors. Simulation results are presented for the different control designs.

1.3 Platoon Formation Control

Vehicle platooning is a form of formation control. This can be compared to many animals that exhibit swarm behavior in the world. A swarm is a group of animals that work together to achieve some common goal. These distributed agents have only local knowledge and communication. Such local interactions and each individual agent's behavior cause a global *"emergent behavior,"* which allows these agents to form the desired shape. The control algorithm then maintains this shape with least deviation. The same concept is utilized in platooning wherein vehicles communicate with each other to remain in the formation. Robots have been used extensively in formation control to analyze control strategies. In this research, the LEGO mindstorm NXT 2.0 was used to demonstrate this behavior of vehicles.

This type of formation control involves lateral control as well as longitudinal control. In lateral control, the basic goal is lane keeping. It can also be called "steering actuator control." In the California partners for advanced transit and highways (PATH) program, magnetic markers embedded along the center of the road 4 feet apart were used to keep the vehicles at the center. Sensors on-board the vehicles measured corresponding physical properties of the magnetic markers to determine the vehicle's location with respect to the magnetic markers. This information is then processed by an onboard intelligence to generate steering commands for the actuator. Another use of these markers is that just by alternating the polarities of the magnetic markers, information such as upcoming road geometry and entrance or exit data can be transmitted to the vehicles. By comparing the measured magnetic strength to the magnetic field map of a magnet, the relative position of the vehicle is determined. Longitudinal control aims at keeping the vehicles in a platoon as closely spaced as possible, with only a few meters gap between them. In California PATH, eight vehicles traveled in a platoon with fixed inter-vehicular spacings of 6.5 meters between them, at highway speeds. Shorten the inter-vehicular spacing, and more highway capacity is obtained. Inter-vehicular spacing is maintained by means of radar and wireless communication between cars. The velocity and acceleration information of the lead vehicle and the preceding vehicle is broadcasted to each car. Using this information, longitudinal control system generates the throttle or brake command.

1.4 Hardware and Software Platforms

In the beginning of this project, work began on the MASnet platform, developed at CSOIS. The goal was to demonstrate vehicle platooning on the MASnet platform using the MASmotes. This platform utilizes the concept of wireless sensing and actuation on a distributed environment. By regularly updating these sensors and actuators, a closed-loop system, also known as cyber-physical systems (CPS), can categorize and track dynamic environments. These distributed sensors and actuators are networked together to coordinate with each other to monitor and control the environment. This network is known as the wireless sensor network (WSN), in the thesis by Rounds [5]. WSN's have low-power consumption, low cost, mesh networking, and low-data throughput. However, due to old software versions and version mismatches, compilation of codes led to a lot of errors. A great deal of time was spent to solve these errors and get the system running. However, missing files led to discontinued work on the MASnet platform.

The new platform adopted was the LEGO mindstorms NXT 2.0. These were easy to use, had the advantage of programming flexibility and design flexibility. The programming softwares used for the LEGO's included Matlab 2012a and the laboratory virtual instrumentation engineering workbench (LabVIEW) softwares. With the new platform, lateral and longitudinal control with inter-vehicular communications could be demonstrated.

1.5 Outline of Thesis and Contribution

The major contributions of this thesis can be categorized as follows:

- An exhaustive literature survey of vehicle platooning is presented which covers work done in the fields of:

    1. Inter-vehicular communication methodologies,
    2. Lateral and longitudinal control strategies,
    3. Obstacle detection and collision avoidance,
    4. Platoon string stability;

- Simulation studies to demonstrate the stability and robustness of various controller designs and their related performance measures like delay and accuracy;

- Study of the MASnet platform;

- Implementation of platooning on the platform LEGO mindstorm NXT 2.0 using both Matlab and LabVIEW softwares;

- Study the effect of communication delays on platoon string stability.

This thesis has been organized into six main categories, not taking into account the conclusions. The introductory chapter encompasses a brief overview of vehicle platooning and AET, including the benefits of both.

Chapter 2 provides a complete literature survey of vehicle platooning in relation to the topics mentioned above. This literature survey was conducted as a requirement under the grant obtained from DOE.

Chapter 3 describes in detail the MASnet platform developed at CSOIS, along with a description of the softwares issued faced.

Chapter 4 describes the new platform, the LEGO mindstorms NXT, and related work done on them to demonstrate vehicle platooning.

Chapter 5 describes various control strategies studied and simulated along with their effects on performance measures like response time, delays, robustness to uncertainties, and accuracy.

Chapter 6 describes fractional methods for achieving vehicle formation control, and also shows the improved performance of fractional controllers over conventional integer controllers.

Chapter 7 defines "string stability" and related issues. Effect of communication delays on string stability is analyzed in this chapter.

Chapter 8 is the conclusion and future work.

Chapter 2

Vehicle Platooning Survey and Categorization

2.1 Introduction

In this chapter, the vehicle platooning literature published since 1994 is categorized and discussed. The paper includes a general introduction and overview of vehicle platooning and a technical description of the methodology. Recent trends in vehicle platooning are presented and discussed. The results are reviewed and the vehicle platooning literature is categorized into subcategories within the broader division of application focused and theory focused results. Issues and challenges faced in platooning are discussed in the context of AET. A brief summary of the survey methodology is presented.

2.1.1 Definition of Platooning in Literature

In platooning,"linked" vehicles are created which travel along the AHS as one unit. With very small headway spacing, as little as a few meters, these vehicles follow each other, and are connected with some headway control mechanism, such as radar-based or magnetic-based systems. The leader of the platoon continuously broadcasts to the following vehicles, information on the AHS conditions and the maneuvers that the platoon is going to execute. These vehicles travel in close coordination under fully automated longitudinal and lateral control. A constant fixed spacing is maintained between all platoon members at all speeds, upto highway speeds. This short spacing results in increased highway capacity. Automation and coordination between vehicles lead to increased safety. Even extreme accelerations and decelerations cannot cause serious impacts and compromise passenger comfort, since the relative speed between vehicles is small, as shown in Levedahl et al. [4]. This was shown to be true when the platooning scenario was presented by the PATH program in Desoer et al. [6]. Eight automated cars were platooned with inter-vehicular distances under ten meters.

They traveled in a single line formation, laterally controlled by magnets embedded in the roadways. This platoon showed the ability to start, stop, accelerate, and decelerate, as a unit. Furthermore, this platoon also demonstrated the ability to split, to allow the entry of vehicles and then rejoin as one platoon. A heads-up-display unit was used to communicate information such as speed, distance to destination, and the current maneuver of the vehicle, to the driver. Thus, it can be said that vehicle platooning is an approach to improve the current transportation system, both economically and technologically. Ünsal [7] says that there are two main approaches for the implementation of an AHS, hierarchical structure, and autonomous vehicle approaches, of which the first approach is centered around the concept of platooning. In this approach, different layers of control hierarchy are responsible for performing different tasks needed to implement an AHS.

2.1.2 Evolution of Platooning

The present scenario which is seen in AHS has evolved over many years into what today is known as vehicle platooning. There is a very distinct pattern seen in this evolution. At the beginning was the independent vehicle or free agent concept, wherein all smart technology was put into the vehicle and the vehicle acted individually more like a free agent, or a one vehicle platoon. Lack of the need of infrastructure support allowed this vehicle to be used on any existing highways. Then came the cooperative concept which introduced inter-vehicle communication into the free agent concept. This led to the capability of coordination of the vehicle's driving operation. This concept further evolved into the infrastructure supported concept. This was better than the cooperative concept since it provided dedicated lanes for the operation of smart vehicles. Smart infrastructure embedded into these lanes could provide global information regarding the system, needed for the vehicle decision making and operation. This further evolved into the infrastructure assisted concept, wherein inter-vehicle communications (IVC) was provided at the entry, exit, and merging maneuvers by the roadside system that was fully automated. Finally, there was the adaptive concept, which needed different location requirements, and hence, standards were created which left the solutions and decisions free for the localities. Currently, the ongoing project on platooning is the European Union funded safe road trains For environment (SARTRE). Launched in 2009, the 3-year SARTRE project launched its first test in December 2010. This project will wind up in 2012. According to the project director of intelligent transport systems, technically the SARTRE platooning could be ready for rollout in 10 years as said by Kesting [8].

2.2 Technical Overview of Platooning

The feasibility of the usage of a vector field for autonomous navigation has previously been demonstrated by Borenstein and Koren [9]. The technology of way-points and obstacles was used by Levedahl et al. [4]. The way-points exhibited attractive forces and obstacles exhibited repulsive forces which combined to produce a resultant vector indicating the desired velocity of the vehicle. At every point of space, navigational information is provided by this vector field. After obtaining the vector field of a specially designed track, the appropriate points were flagged as track elements and the velocity vector at each track element was set to be the normalized distance vector between that element and the next closest track element. At every other point, the vector is taken to be the linear combination of the distance vector between that particular point and its projection onto the track and the the vector at the nearest track element.

$$v_{des}(r) = \alpha(proj_t(r) - r) + \beta v_t, \tag{2.1}$$

where r is the point at which desired velocity vector v_{des} is calculated, v_t is the velocity vector at the nearest track element, α, β are simulation parameters; and

$$proj_t(r) = \frac{\langle r, t \rangle}{\langle t, t \rangle} t, \tag{2.2}$$

is the projection of r onto the track vector, t. For simulation, $\alpha = 1, \beta = 1.2$. The vector field looks like in Fig. 2.1.

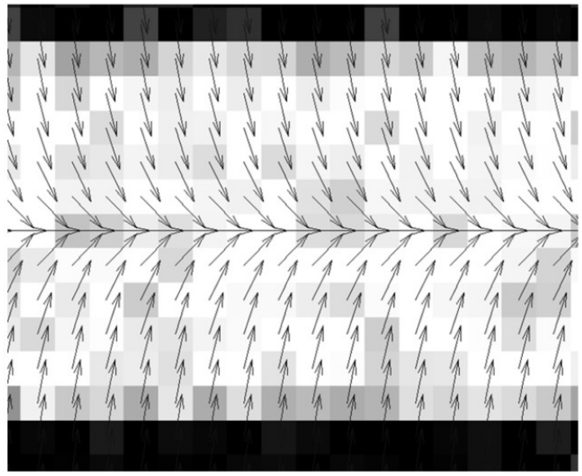

Fig. 2.1: Navigational vector field generated.

2.2.1 Leader Navigation

Leader navigation was achieved by using the feedback of the velocity error, attenuated by α and then supplied as acceleration $a(t)$ of the platoon leader at every time step as seen in Eq. (2.3) and Eq. (2.4).

$$v_{error} = v_{des}(t) - v_{veh}(t) \tag{2.3}$$

$$a(t) = \alpha v_{error}(t) - \frac{F_{friction}(t)}{m_{veh}} \tag{2.4}$$

The final positions of the vehicles are calculated using the standard equation of motion given as

$$s_f = s_i + v_i \Delta t + \frac{1}{2} a (\Delta t)^2, \tag{2.5}$$

where Δt is the time step and v_i is the vehicle's velocity at the beginning of the time step.

Further, according to Kesting [8], the "desired minimum gap" is given by

$$s^*(v, \Delta v) = s_0 + vT + \frac{v \Delta v}{2\sqrt{ab}}, \tag{2.6}$$

$\Delta v = v_\alpha - v_{\alpha-1}$, where α is the following vehicle and $\alpha - 1$ is the leader vehicle, s_0 is the minimum distance in case of congested traffic, a is the maximum acceleration, and b is the "comfortable deceleration." The last term in Eq. (2.6), however, is significant only in nonstationary traffic, when $\Delta v \neq 0$. vT is a term more relevant to the resultant spacing in stationary traffic as shown by Fernandes and Nunes [10].

Also, according to Fernandes and Nunes [10], the formulation to determine road capacity, which can be increased by tighter spacing between vehicles, is given as

$$C = V \frac{n}{ns + (n-1)d + D}, \tag{2.7}$$

where d is intra-platoon spacing, D is inter-platoon spacing, s is vehicle length, and V is the steady state speed in m/min.

2.2.2 Follower Spring Dynamics

Demonstrations of the implementation of collision avoidance modeled on physical systems have been put forth by many researchers, from potential fields by Khatib [11], to fluid dynamics by Decuyper and Keymeulen [12] and spring dynamics by Quinlan and Khatib [13]. However, Levedahl et al. [4] utilized the concept of spring dynamics, wherein only the platoon's leader is provided with navigational information, including the vector field, and the following vehicles are linked together via spring dynamics. It was seen that although this method did manage to keep the vehicles on the track, the more desirable approach is to provide all the vehicles in the platoon with navigational information and have the spring forces act as either amplification or attenuation factors for the vector field, depending on vehicle proximity. Hooke's law for an ideal spring exerting a restoring force is given to be

$$F = -kx, \tag{2.8}$$

where x is the distance between two vehicles, and k is the spring coefficient.

2.2.3 Inter-Platoon Dynamics

For inter-platoon dynamics, a proportional controller was examined by Levedahl et al. [4] which activated when a threshold distance was reached between the lead vehicle of a platoon and the last vehicle of the platoon with which it wished to merge. Details on a nonlinear approach to the inter-vehicle dynamics was studied by Levedahl et al. [4].

2.3 From 1994 to 2012: An Overview

In this section, an overview of the results obtained from the literature search are given. The statistics presented in this section may vary. Nonetheless, all the relevant Ph.D dissertations found have been included. There have not been many previous reviews and surveys on vehicle platooning. Of particular note, however, is the survey conducted by Tsugawa [14] which gives a thorough analysis of the control algorithms in AHS with references through 1965.

The present survey began with a search on "IEEE Xplore," "Web of Science," and "ScienceDirect" sites conducted on October 2010. Table 2.1 shows the search results. As shown in Table 2.1, from the keywords ("Vehicle and Platooning"), we have a total of 284 publications. A broader search was also carried out using the keywords ("Automated" and "Highway" AND "Platoon" and "System") from which we have a total of 134 publications. We also searched under a related topic using the keywords "Vehicle Strings" from which we obtained 231 publications, and "Platoon String Stability" from which we obtained a total of 110 publications. These results can be seen in Table 2.1. Given these large numbers of publications in this paper, our review is restricted to the literature obtained by searching under the phrases "Vehicle Platooning," "Inter-vehicle communication in vehicle platooning," and "Obstacle detection and collision avoidance in vehicle platoons." Other than IEEE conferences, we also include papers published in other conferences like SICE conferences, mechatronics conferences, IEICE conferences, and the SAE conferences.

Figure 2.2 gives a graphical depiction of the number of vehicle platooning publications since 1994 in international conference proceedings and journals.

2.4 Vehicle Platooning Related Ph.D Dissertations and Master's Theses Since 1994

In this section, we will briefly review some Ph.D dissertations and master's theses published in since 1994. Table 2.2 gives an overview of some statistics in this regard. Platoon

Table 2.1: Vehicle platooning related publications from web of science, IEEE xplore, and sciencedirect.

Search Options	From Web of Science	From IEEE Xplore	From ScienceDirect	From Scopus	Total
Vehicle+Platooning	55	118	224	178	575
Vehicle Platooning Dynamics	20	23	110	11	164
Platoon String Stability	33	51	72	71	227
Vehicle Platooning and Communication	15	70	108	55	248
Vehicle Platooning and Collision Avoidance	3	16	54	16	89

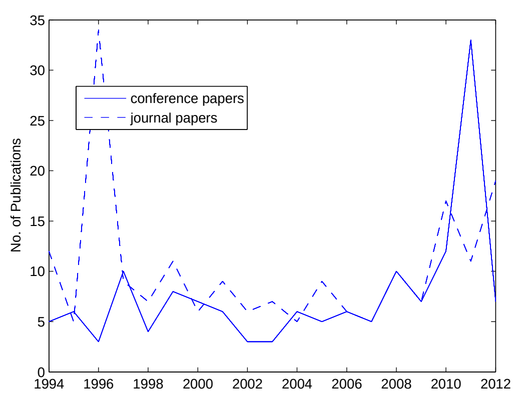

Fig. 2.2: Number of vehicle platooning related publications in conference proceedings and journals.

Table 2.2: Vehicle platooning related Ph.D dissertations and masters theses.

Year	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	Total
Number	2	0	1	2	0	1	3	0	1	0	1	3	2	2	5	3	2	2	2	32

size remains limited by communication, so there is a need for advances in low bandwidth control techniques. Sylvester [15] examined a decentralized, low bandwidth control of an arbitrarily large platoon of autonomous underground vehicles. Dao [16] discussed the design and experimental results of low-cost lane level positioning system that can support a large number of transportation applications. Using a Markov-based approach based on sharing information among a group of vehicles that are traveling within the communication range of each other, the lane positions of vehicles can be determined. The robustness and effectiveness of the system is shown in both simulations and real road tests. Also, a decentralized approach to lane scheduling for vehicles with an aim to increase traffic throughput while ensuring the vehicles exit successfully at their destinations is presented by Dao [16]. The work evaluates a proposed strategy which assigns vehicles to platoons by solving an optimization problem. A linear model for assigning vehicles to appropriate platoons when they enter the highway is formulated. Simulation results are presented to demonstrate that lane capacity can be increased effectively when platooning operation is used. Rajamani studied the use of computational fluid dynamics (CFD) for understanding convoy aerodynamics and airflow interaction between vehicles via CFD. In this study, time-averaged characteristics of a simplified, generic passenger vehicle, called the Ahmed car model, was investigated computationally. Three different platoon combinations were analyzed for the study which included two, three, and six model platoon for various rear end configurations of the Ahmed model geometry. Roberson [17] studied the inter-vehicle communication issues, such as sharing information via limited bandwidth channels and selecting network architecture to facilitate control design for an autonomous underwater vehicle platoon with limited communication. The effects of various communication delays on string stability are analyzed by Mahal [18]. Longitudinal maneuvers for platoons in an AHS are analyzed by Chen [19]. The interaction between control and communication portions of the vehicle software structure is defined.

A complete nonlinear hybrid controller was developed to control the lead modes, follower modes, join transitions and split transitions of an automated vehicle.

A large amount of research work has been done on inter-vehicle communication networks. In the thesis by Böhm [20], the multi access channel (MAC) solution is further enhanced by introducing a prioritization mechanism based on vehicle positions and the overall road traffic density, which further improves the throughput of both real-time and best effort data traffic by focusing the communication resources to the most hazardous areas of the road infrastructure. Various MAC methods are also evaluated. In depth study of 5.9 GHz dedicated short range communications (DSRC) has been done in the thesis by Chrysler [21]. In this master's thesis, a vehicular safety communication architecture is designed, an effective broadcast message distribution scheme is introduced, a channel switch protocol is presented, and a communication stack is proposed. In the thesis by Shooshtary [22], a simulation environment is developed in Matlab for vehicle-to-vehicle and infrastructure communication based on IEEE 802.11p, which is the wireless access in vehicular environments (WAVE) protocol. In the thesis by Hallé [23], a hierarchical driving agent architecture based on three layers (guidance layer, management layer, and traffic control layer) is proposed, which can be used to develop both centralized and decentralized platoons.

Recently, in a master's thesis on vehicle platooning by Nilsson [24], sensor fusion for heavy duty vehicle platooning is studied. To get an accurate estimate of relative velocity and distance, both needed for controller, sensor fusion is necessary. In this thesis, a sensor fusion framework from on board sensor information and other vehicles' sensor information is developed using a wifi link. Another thesis that targets heavy duty platooning is by Kemppainen [25]. In this thesis, a model predictive controller is developed for platooning. The implementation of two types of model predictive controllers (MPC), centralized and decentralized, and then integration with two other subsystems is evaluated in this thesis. It was seen that with a spacing of 10 meters, the energy consumption was reduced when driving at different velocities, with an average of 11%. A thesis that contributes to a framework for the design and implementation of heavy duty vehicles (HDV) platooning is the one by Alam [26]. The thesis focuses on establishing and validating real constraints for fuel efficient platoon control. Results showed a fuel reduction of 4.7-7.7% depending on inter-vehicle time gap, at a set speed of 70km/h. A thesis from the same school as the one above is by Liang [27], wherein a linear quadratic controller (LQR) controller is designed for platoon control.

2.5 From 1994 to 2012: Categorization

In this section, we separate the literature into two different parts. The first part is related to the literature that focuses on vehicle platooning applications and the second part is related to the literature focused on theoretical developments. It is difficult to separate the literature into these two parts, so the categorizations in this section are largely based on the authors' subjective opinions.

2.6 Literature Related to Vehicle Platooning Applications

Since it was difficult to find a variety of applications related exclusively to platooning, the search was widened to also include applications related to key concepts involved in platooning like "inter-vehicle communication" and related issues like "intelligent" and "unmanned vehicles." Kasai and Onoguchi [28] examined an application related to image processing, wherein they present a solution to the challenge of lane detection studied by He et al. [29] in vehicle platooning which helps overcome the problem conventional methods face when processing the image captured from a front camera. The proposed method has been implemented on the image processing hardware whose central processing unit satisfies on-board specifications. Another application of platooning was seen in mobile robots as demonstrated in different papers by Sakaguchi et al., Ferrara, Crawford et al., Michaud et al., Freslund and Mataricx, and Das et al. [30–35]. DellaVedova et al. [36] describe a robotic application where a coordinated team of mobile robots moves as a platoon. Particularly, the use of a real time operating system which implements the control algorithm running on-board for each robot was demonstrated to assess the impact of real time parameters of computing tasks on the performance of the control application.

Platooning has some interesting applications for autonomous vehicles in intelligent transportation systems. Guldner et al. [37] analyze the challenge of communicating information from infrastructure to vehicles. Use of magnetic markers as discussed by Lee et al. [38], enables binary coding for information exchange from roadway to vehicle, to be utilized for AHS subtasks.

In a platoon of vehicles, detection of overtaking vehicles plays an important role in safety. Early detection of overtaking vehicles is analyzed by Zhu et al. [39]. Related to this application, important categories were identified as "blind spot monitoring" and "lane change support." Older people generally lose flexibility in their neck, making it harder to check before changing lanes, so intelligent sensors that monitor the blind spot can allow seniors to drive safely. This is studied by Aufrere et al. [40]. In addition, the U.S. military has increasing interest in intelligent vehicles. Scout vehicles typically operate in front of the main force and are the first target of the opposition. It is hence desirable to have autonomous scouts that can investigate hazardous areas leading to increased safety of soldiers,as demonstrated by Aufrere et al. [40]. Additional applications like "cooperative robot reconnaissance," studied by Balch and Arkin [41]; "manipulation," studied by Ogren et al. [42]; "formation flight control," studied by Mesbahi and Hadaegh [43]; "satellite clustering," studied by Giulietti et al. [44]; and "unmanned vehicles," studied by Stilwell and Bishop [45] have also been seen in literature. A major application of platooning is seen in roadside safety. "Automatic car parking" is also suggested as an application by Klancar et al. [46]. Willke et al. [47] conducted a detailed survey of inter-vehicle communication based applications and examples of applications like "truck platooning," "coordinated braking," "runway incursion prevention," "vehicle formation control," and "adaptive traffic control" are cited. These applications are grouped into two types of classes according to the aim, whether "safety information services" or "individual motion control." Willke et al. also surveyed specific applications in the literature and classified the examples of IVC into four classes.

Also included are applications of platooning in the agricultural sector as studied by Zhang et al., Zhongxiang et al., Keicher and Seufert, Benson et al., and Noguchi et al. [48–52]. Since the demands on agricultural productivity are increasing while there is a desire to decrease the labor force, automation of agricultural machinery plays an important role. Platooning of tractors for automation of agricultural tasks like ploughing and sowing is studied by Zhang et al. [48]. Platooning application can be extended to aerospace systems as seen in the book by Samad [53]. For example, flight formation control for uninhabited combat air vehicles (UCAVs) with fleet coordination and autonomy is talked about by Samad [53]. Girard et al. [54] present a group of coordinated autonomous underwater vehicles which can search for a coastal area of mines more efficiently. Related to this application, detailed categories were given as "oceanographic surveys" in the thesis by Gird [55], "operations in hazardous environments" by Bellineham et al. [56], and "underwater structure inspection" by BorgerdeSoura et al. [57].

Applications of platooning in railway systems have been proposed and studied by Henke et al. [58]. In the case of rail-bound vehicles, only the control of the longitudinal dynamics is required with respect to drive control. The RailCab project, founded at the University of Padeborn in 1998, is studied wherein the RailCab convoy is built from single RailCabs. Recent work on improving fuel economy was studied by Alam et al. [59]. An interesting observation in this paper is the reduction in fuel consumption with adaptive cruise control in operation, with prior information feed about the road map from the leader. Comparing experimental results for different masses of lead vehicle, a key result obtained here is the variation in fuel consumption based on the time gap. Figure 2.3 summarizes the occurrence of different applications in the platooning literature.

2.7 Literature Related to Vehicle Platooning Theories

It was seen that the literature related to theoretical developments was broadly classified into following subcategories listed below:

- Inter-vehicle communication methodologies,

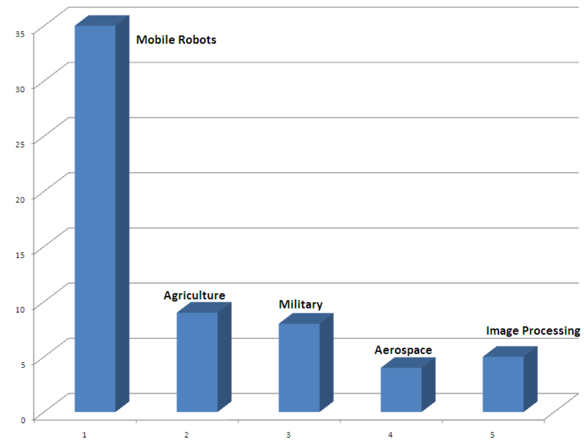

Fig. 2.3: Publication number of application focused platooning results.

- Collision avoidance and obstacle detection methodologies,
- Design of lateral and longitudinal control systems for a platoon,
- String stability of a platoon.

Different techniques have been implemented so far for sensing and detection of obstacles, inter-vehicle communication and the control algorithm implemented. A brief survey of these techniques are presented here. Figure 2.4 shows statistical results from the survey.

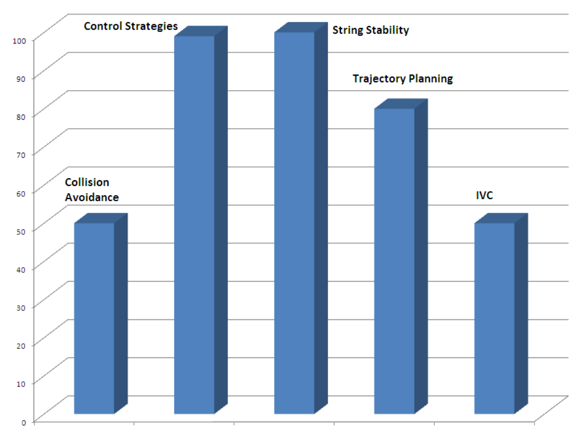

Fig. 2.4: Publication number of theory focused platooning results.

2.7.1 Obstacle Detection and Collision Avoidance

Inter-platoon cooperative collision cvoidance (CCA) systems form an important aspect of "vehicular ad-hoc networks" (VANET) safety applications. An efficient CCA strategy based on a risk-aware MAC protocol tailored for VANET networks has been proposed by Taleb et al. [60]. In this system, the vehicles were first clustered according to the features of their movement using information like direction of movement, inter-vehicle distance, and relative speed. An emergency level was associated with each cluster which indicated the likelihood a vehicle would experience an accident in the platoon. In another paper, a broadcast based packet forwarding mechanism for inter-platoon CCA using DSRC was proposed by Tatchikou et al. [61]. Another publication that talks of DSRC in platooning is by Fernandes and Nunes [62]. The problems faced in using DSRC when performing platooning are targeted here. To solve this issue, this paper proposed a new IVC based on a combination of DSRC and infrared.

Gehrig and Stein [63] have proposed the concept of elastic bands and analyzed collision avoidance. The original elastic band approach was proposed by Quinlan and Khatib [13]. Forces acting on the elastic band are computed by taking the gradient of the potential energy at discrete path points. The repelling forces on the elastic band are produced by obstacles in the vicinity of the path. The path the leader follows is the initial path and obstacles in the environment exert forces on the band and move it into a final configuration. This is the path followed by the following vehicles.

The development of a rear end collision avoidance system has been analyzed by Araki et al. [64] where the system had automatic braking when the headway distance between the trailing vehicle and the selected vehicle crossed the safety threshold. It informs the driver of distance headway and warns the driver when there is a potential collision hazard. While the problem of cruise control has been deeply explored by researchers, more work still needs to be done on the possibility of enriching the control system of the vehicles with the ability to autonomously react to the presence of any moving or static obstacles on the road. This issue is investigated by Ferrara and Vecchio [65] where a cruise control system with collision avoidance features is proposed. The concept used by Ferrara and Vecchio [65] involves the idea of a supervisor for the control system of every vehicle in the platoon. The supervisor receives data from the car's sensors. Whenever new data is collected by the sensors, the supervisor of each vehicle performs a collision detection test which relies on the concept of a collision cone, studied by Chakravarthy and Ghose [66]. When a possible collision is detected, the control system switches from the normal "cruise mode" to "collision avoidance mode," causing the involved vehicle to stop following the preceding vehicle. The decision to switch involves which action to take from emergency braking and the generation of a collision avoidance maneuver. For this, two low-level controllers were implemented. A sliding mode control methodology was used for the two controllers.

Concerning automatic platooning, processing can be done based on

- the use of radar only;
- the fusion of an active sensor (laser, radar, lidar) and monocular vision, studied by Steux et al. [67];
- monocular vision only.

A very widely used approach for monocular vision-based vehicle detection analyzed by Betke et al. and Kyo et al. [68, 69] is to search for specific patterns as shown by Bertozzi et al. [70]. These patterns could be the shape, analyzed by Xiong and Debrunner, and Fung et al. [71, 72]; motion, analyzed by Demonceaux et al. [73]; color, analyzed by Steux et al.; Xiong and Debrunner [67, 71]; symmetry, analyzed by Steux et al. and Hoffman et al. [67,74]; shadow, analyzed by Steux et al. and Tenakte et al. [67,75]; texture, analyzed by Tenakte et al. [75]; or the use of a specific model, analyzed by Gregor et al. [76]. Bertozzi et al. [77] developed a stereo vision algorithm specifically tailored for vehicle detection. Recent work on localization using monocular vision was done by Avanzini et al. [78]. Since some sensors are very expensive, and localization data can only be obtained in the virtual vision world. Avanzini et al. [78] proposed a strategy to obtain this data using monocular vision and correcting it by removing the distortions.

Model-based vehicle detection was analyzed by Collado et al. [79], wherein a computer vision system based on a geometric model is developed for vehicle detection. The shape and symmetry of the vehicle, along with the shadow it produces, are used to obtain the energy function of the system. Denasi and Quaglia [80] limited the processing to the image portion that is assumed to represent the road; borders that could represent a potential vehicle are looked for and examined. Lützeler and Dickmanns [81] studied an edge detection process with obstacle modelization. This system is able to detect and track up to twelve objects around the vehicle. Broggi et al. [82] used stereo images for the identification of free space in front of the vehicle and showed this method to be robust for obstacle detection. Use of graph theory for collision avoidance has been analyzed by Gowal et al. [83]. The active collision avoidance mechanism implemented here uses both lateral and longitudinal axes. The vehicles not only avoid road obstacles but also themselves when converging to the desired formation.

Detection of obstacles based on multi sensor fusion between lidar and radar was proposed by Okada and Suganuma [84]. The detection of the lane where the obstacle is present is done using a digital map, obtained from lane markers.

2.7.2 Inter-Vehicle Communication

Inter-vehicle highway systems (IVHS) architecture also provides a communication system which allows vehicles on the highway to share driving information such as the velocity and acceleration of each vehicle, road condition estimates, and obstacles detected by the lead vehicle.

One of the earliest studies on inter-vehicle communications was that started by Association of Electronic Technology for Automobile Traffic and Driving (JSK) in Japan in the early 1980s, as demonstrated by Tsugawa [85]. It was originally defined as flexible platooning of automated vehicles, also named super smart vehicle system (SSVS). Several different IVC models were designed, implemented, and tested in the last decade. Some of the most notable are cooperative optimized channel access for inter-vehicle communication (COCAIN) as impemented by Kaltwasser and Kassubek [86], telecommunication network for cooperative driving (TELCO) implemented by Verdone [87], and dedicated omni-purpose inter-vehicle (DOLPHIN) communication protocol implemented by Tokuda et al. [88]. A previous survey on inter-vehicle communications worth noting is that conducted by Sichitiu and Kihl [89] which also analyzes applications of IVC.

Infrared and radio waves have been studied as the media for IVC and employed for experimental systems. The radio waves include very high frequency waves (VHF), microwaves, and millimeter waves. The communications with infrared and millimeter waves are line-of-sight and usually directional whereas those with VHF and microwaves are used for broadcasting. Although VHF waves have been used because of their long communication distance, microwaves are predominantly used today.

A system which uses 220 MHz band (the VHF wave) has been proposed by Fitz et al. [90]. Its objectives are safety related systems including an incident warning system. Since the communication range is 1-2km, the system is feasible even if the penetration rate of the communication unit is low. The communication system is also applied to a "chat" system among drivers relayed with a base station on the ground.

Mobile phones can also be used for inter-vehicle communication. A consortium in Germany proposed a system that transmits information about an accident or similar incident detected by a vehicle to following vehicles through mobile phones using the localization data provided by the accompanying global positioning system.

As mentioned earlier, microwaves are used in several systems, including the Demo 97 in San Diego and in truck platooning named "Chauffeur," developed by Daimler Chrysler, as cited in Gehring and Fritz [91] where commercially available wireless radio was employed for vehicle control. At the beginning of the Chauffeur project, the 2.4 GHz wave was used for the inter-vehicle communications. The communication period was 40 ms, and the transmission rate was 230 kbps. Data transmitted by vehicles included speed, acceleration, and the intention of joining or leaving the platoon. Later, the inter-vehicle communications for Chauffeur were updated to the 5.8 GHz band.

Another medium used for inter-vehicle communications is infrared which is again generally line-of-sight. Infrared was employed in the cooperative driving phase I of JSK by Fujii et al. [92]. In this system, a preceding vehicle was equipped with infrared markers on the roof. One marker functioned as a transmitter and both functioned for inter-vehicle distance measurement with triangulation. The feature of this system was that the following vehicles could communicate with preceding vehicles as well as measure the inter-vehicle distances. Yet another system was developed by California's PATH wherein the communications were performed between two vehicles using transceivers located on the bumpers of each vehicle. The feature of this system was that the transmission rate was controlled by observing the bit error rate; if the inter-vehicle distance is short, the bit error rate is small, so then the transmission rate can be increased and vice-versa.

Cooperative vehicle-to-vehicle communication plays a key role in keeping the relative spacing of vehicles small in a platoon. Static platoon control, where the number of vehicles remains constant, is sufficient for the information to be transmitted in a suitably fixed interval. Dynamic platoon control, such as for a merge or split, requires a more flexible network architecture for the dynamic coordination of the communication sequence. Kim and Choi [93] used a low-cost, short range industrial, scientific and medical (ISM) band transceiver and 8-bit microcontroller to implement a wireless communication device and reliable communication protocol.

In a platoon, the information of the preceding vehicle can be obtained using the range radar. This information is not available for other members of the platoon, only the leader. Such a scheme guarantees that each vehicle in the platoon has a chance to transmit its information every cycle in the case of static platoon control. However, for dynamic platoon control, the maneuvering vehicle requires frequent update of the control input so more information needs to be transmitted to the maneuvering vehicle. This coordination of the communication sequence is achieved by remote control stations (RCS) by Kim and Choi [93]. To reduce the effect of unreliable wireless data access in vehicular networks, a new system based on "vehicle platoon aware access solution" is proposed by Zhang and

Cao [94]. Simulation studies in this paper have shown this solution to improve data access in VANET's to a considerable extent. The 433 MHz RF-module, BIM-433, is used for the implementation of the wireless communication system of the time division multiple access (TDMA) with token passing architecture. The data transfer rate of this RF-module is 38 kbps and the carrier sense algorithm is not supported. Also, for stable movement of each vehicle, the sampling period of a vehicle should be less than 40 ms according to Kim and Choi [93].

It is generally more effective to use a TDMA method or a round robin method to avoid collision and interference of packets during communication. However, a TDM method requires knowing the maximum number of vehicles in a platoon in advance to prepare the slots, which is challenging for realistic platooning where vehicles can join/exit throughout. A new data transmission algorithm is proposed by Uno et al. [95] to solve this problem. In this algorithm, the order of data transmission from a vehicle to another is not based on the physical order of vehicles in the platoon. Instead, a round robin method is used.

An experimental system of 60 GHz millimeter wave band inter-vehicle communication system based on DOLPHIN protocol was implemented by Tokuda et al. [88] and a carrier sense multiple access (CSMA) used Spread Spectrum (SS) was implemented by Maeda and Nakagawa [96].

An interesting concept using IVC was proposed by Kesting et al. [97]. Here, instead of using the information in the conventional manner, an alternative mode is proposed wherein the data is stored by relay vehicles, which are traveling in a direction opposite to that of platoon flow. This data is then forwarded to the platoon after some delay. Stabilization of discrete time networked control systems is very crucial when is comes to platooning. Xiao et al. [98] showed that there is a requirement on the network over which an unstable plant can be stabilized. Safe platooning without the use of communications has also been studied by Scheuer et al. [99]. The model in this paper is derived by studying the most dangerous interaction between vehicles. The leader's maximum acceptable acceleration is considered when the previous vehicles all brake at maximum capacity. Proof of collision avoidance for this model is also given.

Another communication topology based on a multicast methodology for a platoon is proposed by Kanda et al. [100]. This is targeted toward improving intra-platoon communications. A very interesting concept was studied by Caveney and Dunbar [101]. Instead of utilizing IVC for information sharing, it is also used for shared decision making between platoon members. A "distributed receding horizon control" is proposed for achieving this.

2.7.3 Protocol

A list of the various protocols used in the different projects has been given by Jawhar et al. [102]. A survey of both vehicle-to-vehicle and vehicle-to-infrastructure communication protocols is also provided. There are two requirements on the protocol of the inter-vehicle communication system. The first is that the protocol must be flexible to maintain a network among vehicles when a new vehicle leaves or joins. Secondly, the protocol should be able to deal with real time data transmission. In the newly initiated European project employing the application of infrared, CarTALK 2000, the protocol was based on infrared data association (IrDA). In the cooperative driving phase I with infrared communications by JSK, the protocol was network-oriented. Considering the importance of real time data transmission, the slotted ALOHA was employed by Fujii et al. [92]. In the cooperative driving phase II with 5.8 GHz DSRC, the protocol based on CSMA was used by Tokuda et al. [88]. Another project based on 5.8 GHz DSRC was a national project named "Energy ITS," led by Tsugawa et al. [103]. Here, three trucks were platooned with a lateral system comprising of lane markers, a longitudinal system comprising 76 GHz radar and lidar. Manzano et al. [104] proposed a MAC protocol based on non-cooperative cognitive radio techniques to obtain a mechanism complying with the requirements of real time communications. This technique overcomes the limitations of the WAVE standard. Tank et al. [105] presented a comparison of TDMA, direct sequence CDMA (DS-CDMA), and multi carrier CDMA (MC-CDMA) schemes in an AVCS platoon environment with Rician fading and Rayleigh interference. It was shown CDMA undergoes fast fading while TDMA undergoes slow fading. Packet erasure rates were found in order to measure the performance of these multiple access schemes. It was also shown that bandwidth considerations must be taken into account when evaluating the performance of each scheme.

2.7.4 Control Strategies

Much work has been done in the study of longitudinal control problems as a part of the AHS program and a variety of solutions have been presented. A good overview of these activities is given by Shladover [106]. Sheikholeslam and Desoer [107] used feedback linearization techniques, in combination with linear control laws, to obtain a stable longitudinal vehicle platoon. Adaptive control methods are presented by Yanakiev and Kanellakopoulos [108] to cope with the nonlinear system behavior of heavy duty vehicles and to achieve string stability which ensures that position errors do not propagate down the platoon. Choi and Hedrick [109] presented a nonlinear sliding controller with a multiple surface technique and the successful operation of the control system is demonstrated with practical results given for a 4-car platoon. Demonstration of robust control using sliding mode controllers is also discussed by Ferrara et al. [110].

The control algorithms used by PATH in the 1997 eight vehicle platoon demonstration are described by Rajamani et al. [111]. For the demonstration, a hierarchical structure was implemented to provide both longitudinal and lateral control to vehicles within the platoon. Longitudinal control focuses on maintaining constant spacing between vehicles while lateral control addresses the left and right motion of vehicles so they can either maintain or change lanes. The longitudinal control used a high level controller to provide the desired acceleration for each vehicle while a lower level controller determined the actuation needed to achieve such an acceleration. At the upper level of the longitudinal control, a sliding surface controller design method was implemented. The sliding surface for vehicle i as given in Eq. (2.9) is a function of three tunable gains, the velocity of the lead vehicle v_l as well as the preceding vehicle v_i, and the longitudinal velocity error of the i^{th} vehicle $\dot{\epsilon}_i$

$$S_i = \dot{\epsilon}_i + \frac{w_n}{\xi + \sqrt{\xi^2 - 1}} \frac{1}{1 - C_1} \epsilon_i + \frac{C_1}{1 - C_1} (v_i - v_l), \tag{2.9}$$

where S is the sliding surface. ξ, C_1 and w_n are the controller gains that need to be tuned. Each follower determines its desired acceleration on this surface using the communicated velocity and acceleration of both the preceding vehicle and the lead vehicle by setting

$$\dot{S}_i = -\lambda S_i, \lambda = w_n(\xi + \sqrt{\xi^2 - 1}). \tag{2.10}$$

C_1 ranges between $[0, 1]$ and represents the vehicle's dependence on communicated information from the leader. Setting the damping ratio ξ to one represents a critically damped system. The lower level controller in each vehicle then determines the actuation needed to achieve the desired acceleration. Using a physical model of the vehicle engine provided by the manufacturer and basic fluid laws, the desired acceleration can be linked to a corresponding combustion torque and, through use of another sliding surface controller, a desired throttle angle α can be obtained. The authors note that if the necessary torque is negative, the brake actuator provides the torque whereas the throttle is used to generate positive torque.

Vehicle position and orientation are the primary concern of the lateral control system. In the PATH demonstration, each vehicle was equipped with a front and rear sensor to detect the vehicle's placement in relation to magnets embedded under the roadway. The lane keeping controller is comprised of three parts: an integral control to provide a steady-state tracking error of zero, a frequency shaped virtual look-ahead controller, and a servo controller to direct vehicle actuation in response to the anticipated displacement provided by the look-ahead controller. Lane changing is a much more challenging problem and two different schemes are discussed. The first strategy uses magnets between lanes to guide vehicles between in the merging process, thus reducing the control overhead but limiting availability of lane changes. Free lane change is a more generic merge strategy that does not rely on additional infrastructure.

Longitudinal control by adaptive vehicle traction force control (force arising from tire/road interaction) is implemented by Lee and Tomizuka [112]. Two different traction force controllers, adaptive fuzzy logic control and adaptive sliding mode control, are proposed and tested for stable but fast accelerations and decelerations of vehicle platoons. An issue which, if not considered, could be disastrous to a platoon system is that of control saturation. Vehicle platooning naturally implies a saturation problem when nonidentical vehicles are allowed. Warnick and Rodriguez [113] presented a systematic design procedure for adapting a nominal controller, designed without regard to control saturation, to a higher performance nonlinear controller that explicitly accounts for the saturating nonlinearities while preserving stability. A two-layered control structure is proposed by Gehrig and Fridtjof [114]. The inner control loop includes a nonlinear acceleration controller linearizing a large part of the nonlinearities. A robust platoon controller is introduced for the outer control loop by the use of a sliding mode control design. With the proposed control concept, string stability can be achieved in the face of saturation. Systems with combined lateral and longitudinal control systems are important for a well designed platoon system. It is shown that longitudinal controllers that directly control the wheel slip are inherently more stable, especially during lateral maneuvers on very slippery road conditions.

For a platoon of multiple vehicles, lateral error propagation is a serious issue that can be resolved if vehicle performance is compensated. Lateral control is generally achieved by the combined use of road and vehicle infrastructure such as magnetometer and lane marker camera schemes. Lateral platoon stability remains an issue, since the vehicle systems are interconnected. Addition of inter-vehicle communication ensures lateral platoon stability and satisfactory performance since it eliminates the interconnection among the vehicles, provided that the communication delays are sufficiently short.

Stilwell and Bishop [115] proposed an effective decentralized control technique for platoons and underwater vehicles. A lot of research is also being conducted in the application of fuzzy controllers to design the ACC system. ACC systems should be designed such that string stability can be guaranteed. In addition, every vehicle in a string of ACC vehicles which use the same control law should track the arbitrary bounded acceleration and velocity of its preceding vehicle with bounded spacing and velocity errors. Sang and Lee [116] proposed and designed a fuzzy logic based ACC which guarantees string stability. The use of learning control is also studied by Ünsal [7], wherein a "learning automata approach" was shown capable of capturing the dynamics of driver behavior. The controller learns the action in real time instead of learning the parameters or firing rules for deciding the best action to be taken for achieving a safe and optimal path. A 4-layer hierarchical control architecture consisting of network, link, planning and regulation layers, as proposed by Varaiya and Shladover [117], is used in an intelligent controller which can be seen as the planning layer of an autonomous vehicle. The communication between the planning and regulation layers was achieved by having the planning layer issue a command to the regulation layer. The regulation layer in turn returns a reply when the command is carried out. A richer interface could be achieved if the planning layer were capable of sending multiple parameters to the regulation layer, which in turn would return parameters indicating "success" or "errors" and "exceptions." This, however, requires more research on how the regulation layer should switch from one control law to another. Unfortunately, the system had the disadvantage of requiring extensive modifications even for minor changes in rules. The system also failed to handle unanticipated situations.

Tsugawa [14] conducted a complete survey on lateral and longitudinal control algorithms for the AHS with reference to systems developed since 1965. Gowal et al. [83] used a "laplacian feedback control" approach for solving the consensus problem. This approach was also proved to be robust under different realistic conditions. A control strategy that integrates automatic cruise control and cooperative cruise control is presented by Sent*ü*rk et al. [118]. This controller design is robust since it also considers delays and noise in communication channels.

A controller based on the internal model principle is designed by Lunze [119] and is applied to vehicle platooning. Here, it was shown that an appropriate networked controller can be used to obtain a synchronization between leader follower if and only if the agent dynamics include the dynamics of the trajectory.

2.7.5 Platoon Control: A Robust Approach

Much interest has been shown in finding a robust controller for vehicle platooning.

Peng et al. [120] talk of H^∞ control theory for robust platoon control. A robust intelligent backstepping control (RIBC) is proposed for car following platoon control. A cerebellar model articulation controller (CMAC) is adopted in this paper for closed-loop control of dynamic systems due to its faster learning characteristics and computations as compared to neural networks. A "recurrent cerebellar model articulation controller (RCMAC)" is also proposed. The RIBC is comprised of an adaptive RCMAC and an H^∞ robust controller.

Pan [121] applied a robust nonlinear observer and robust output feedback controller to a decentralized control for interconnected systems. The proposed robust control approach with nonlinear observer in this paper ensures convergence of the interconnected system when operated in the region where the system is stable.

Abrishamchian and Modabbernia [122] designed a robust controller for automatic steering using μ synthesis. Here, the nonlinear parametric uncertainties are modeled in a conservative way to form the $P - K - \Delta$ structure.

Alternatively, a linear quadratic controller (LQR) based control for vehicle platooning is analyzed by Liang [123]. LQR control allows for the possibility of extending platoons while maintaining the locally centralized control properties. Dold and Stursberg [124] introduced a distributed predictive control approach for a platoon of vehicles. Here, a robust model predictive control for interconnected systems is analyzed. Min-max optimization is performed where the controller maximizes the cost function with respect to disturbances and minimizes the cost function with respect to the input. Another paper that talks of LQR based design is by Alam et al. [125], which focuses on decentralized control. This is tested for heavy duty vehicle platooning.

2.8 Challenges and Issues in Vehicle Platooning

A very interesting concept was examined by Blum and Eskandarian [126]. Although platooning can decrease travel time, it has certain underlying security issues. Blum and Eskandarian consider the problem of hackers using the system to cause accidents. Due to the utilization of wireless inter-vehicle communication in platooning, which is easily accessible, the system is exposed to computer security attacks. This wireless network can invite denialof-service attacks and alteration attacks on legitimate network traffic, all of which could weaken the system's safety. Because of these weaknesses, attackers could exploit intelligent transportation systems to cause new roadway danger with severe consequences, "intelligent collisions." One way to deal with this is to authenticate the information before it is used by the platoon by keeping a private key. The key is used to authenticate information from sensors before it can be used by the system. Blum and Eskandarian [126] explore the IVC network's potential susceptibilities to attack and emerging research targeted at reducing the impact of such attacks.

Another important consideration is that of communication induced random delays. Hedrick et al. [127] studied the effects of communication delays from the lead vehicle on string stability. They concluded that any delay in the communicated information using the existing control algorithms will result in the platoon no longer being string stable over all conditions. Therefore the authors proposed the development of control algorithms that are robust to communication delays and to random dropouts. Similarly, measurement losses among satellites due to the shadowing effect are addressed by Smith and Hadaegh [128]. A method to handle communication dropouts is studied by Teo et al. [129], wherein, the lead state is propagated for control. In the event of a loss of the lead vehicle state, a propagation of the state is computed and used in the control law. Mathematically, this is written as Eq. (2.11)

$$\hat{v}^i_{l,k} = J^i_k v^{-i}_{l,k} + (1 - J^i_k)\breve{v}_{l,k}, \hat{s}^i_{l,k} = J^i_k s^{-i}_{l,k} + (1 - J^i_k)\breve{s}_{l,k}, \tag{2.11}$$

where l denotes the lead vehicle, $\hat{v}^i_{l,k}$ is the speed of the lead vehicle at the k^{th} time instant, s_i and v_i are the distance traveled and speed for a platoon respectively, $\hat{v}$ is an estimate of v, $\breve{v}$ is a measurement of v and $J^i_k = 1$ implies a lost link between the lead, and i^{th}vehicle at time $k = 0$, and $J^i_k = 0$ implies a good link. Maintaining this notation, the propagation is then given as Eq. (2.12)

$$v^{-i}_{l,k+1} = \hat{v}^i_{l,k} s^{-i}_{l,k+1} = \hat{s}^i_{l,k} + \hat{v}^i_{l,k} T, \tag{2.12}$$

which implies that each vehicle assumes the lead vehicle travels at constant speed during losses.

Vehicle-to-vehicle radio links are bound to suffer from multipath fading as well as interference from other vehicles. These communication links have to be extremely reliable. Jakes [130] and Clarke [131] investigated a vehicle-to-base station Rayleigh fading channel whereas Akki and Haberl [132] investigated a vehicle-to-vehicle Rayleigh fading channel. However, Tank et al. [105] studied the Rician fading channel. From the MAC point of view, the delay in processing is a main cause of packet loss. Multiple access schemes such as TDMA, DS-CDMA, and frequency hopping with TDMA are investigated to determine their performance with regards to packet erasure rates and reliability. It was shown that CDMA gives better results than TDMA. Tank et al. [105] also concluded that deep fades and large probabilities of packet losses can occur for distances less than 3 m due to inherent cancelation of ground-reflected and direct line-of-sight waves. Consequences of communication delays have already been shown by Hitchcock [133] and Shladover et al. [134]. The effect of information delays on string stability has also been studied by Xiong and Feng [135]. Onboard sensors typically operate with a scan frequency between 3-10 Hz. This implies a potential information delay varying between 0.10 sec and 0.33 sec.

Wireless communication systems have the additional problem of delays mainly due to packet losses, transmission times, and the time to analyze and process the transmitted data, as pointed out by Mahal [136]. Most longitudinal controller designs do not take into account the effect of communication delays on string stability. Liu et al. [137] analyze this issue in detail. The robustness of current longitudinal controller designs to communication delays is examined by the author. The radio spectrum directly limits the data rates on the wireless channel. As the signal propagates through the channel, it undergoes random power fluctuations over time due to changing reflections and attenuations. These power fluctuations cause time-varying data rates and intermittent connectivity, thus introducing random delays and packet losses. In the following section, the effects of communication delays analyzed by Liu et al. [137] are summarized.

2.9 System with Communication Delays

The longitudinal controller considered by Liu et al. [137] is a sliding mode control. The spacing error is defined in Eq. (2.13)

$$\epsilon_i(t) = x_i(t) - x_{i-1}(t) + L_i, \tag{2.13}$$

where x_i denotes the abscissa of the rear bumper of the i^{th} vehicle and L_i is the slot allotted to the i^{th} vehicle, (i.e., the desired spacing between vehicle i and $i-1$ from rear bumper to rear bumper). ϵ_i measures the deviation in the assigned distance between vehicle i and $i-1$.

Considering the feedback information contains relative position, velocity, and acceleration of both the lead vehicle and preceding vehicles, define

$$S_i = \dot{\epsilon}_i + q_1\epsilon_i + q_3(v_i - v_l) + q_4(x_i - x_l + \sum_{j=2}^{i} L_j), \tag{2.14}$$

where q_1, q_3, q_4 are design parameters. S_i is a function of ϵ_i. It is desired that S_i approaches zero as ϵ_i approaches zero. By setting

$$\dot{S}_i = -\lambda S_i, \tag{2.15}$$

for some $\lambda > 0$, the control law is given as

$$\begin{aligned} u_{i_d} &= \frac{1}{1+q_3}[\ddot{x}_{i-1} + q_3\ddot{x}_l - (q_1+\lambda)\dot{\epsilon}_i - q_1\lambda\epsilon_i \\ &\quad -(q_4+\lambda q_3)(v_i - v_l) - \lambda q_4(x_i - x_l + \sum_{j=2}^{i} L_j)]. \end{aligned} \tag{2.16}$$

The actuator lag and signal processing delay is modeled as a first order filter

$$\tau\dot{u}_i + u_i = u_{i_d}, \tag{2.17}$$

where τ is the "time constant," taken here as 0.05 sec. Differentiating both sides of Eq. (2.13) results in

$$\dot{\epsilon}_i(t) = \dot{x}_i(t) - \dot{x}_{i-1}(t) = v_i(t) - v_{i-1}(t), \tag{2.18}$$

$$\ddot{\epsilon}_i(t) = \ddot{x}_i(t) - \ddot{x}_{i-1}(t) = a_i(t) - a_{i-1}(t). \tag{2.19}$$

The i^{th} vehicle dynamics are given as

$$\dot{v}_i = u_i. \tag{2.20}$$

Substituting Eq. (2.13), Eq. (2.18), Eq. (2.19), and Eq. (2.20) into Eq. (2.17) gives

$$\tau \frac{d^3 \epsilon_i}{dt^3} + \ddot{\epsilon}_i = u_{i_d} - u_{i-1_d}. \tag{2.21}$$

The time delays in both the preceding and lead vehicle information are defined as

- $\tau_{dp}^{(i)}$ is the timing delay of the preceding vehicle information seen by vehicle i,
- $\tau_{dl}^{(i)}$ is the timing delay of the lead vehicle information seen by vehicle i.

Substituting Eq. (2.16) into Eq. (2.21) and taking the Laplace transform to get the desired transfer function yields

$$\begin{aligned} H_{11} E_i(s) &= \frac{1}{1+q_3}[G_1 E_{i-1}(s) + G_2 A_l(s) \\ &\quad + G_3 A_{i-1}(s) - G_4 A_{i-2}(s)], \end{aligned} \tag{2.22}$$

where

$$H_{11} = \tau s^3 + s^2 + (\lambda + \frac{q_1 + q_4}{1+q_3})s + \frac{\lambda(q_1 + q_4)}{1+q_3}, \tag{2.23}$$

$$G_1 = \lambda q_1, \tag{2.24}$$

$$G_2 = \frac{1}{s^2}(e^{-\tau_{dl}^i s} - e_{dl}^{-\tau i-1} s)(q_3 s^2 + (q_4 + \lambda q_3)s + \lambda q_4), \tag{2.25}$$

$$G_3 = \frac{e^{-\tau_{dp}^i}}{s}(s + (\lambda + q_1)), \tag{2.26}$$

$$G_4 = \frac{e^{-\tau_{dp}^{i-1}}}{s}(s + (\lambda + q_1)). \tag{2.27}$$

For a detailed discussion to distinguish the effects of communication delays in lead and preceding vehicle information, refer to the works of Liu et al. [137]. Currently, there is no controller design that takes these communication delays into account and there is a need to design controllers that adapt to the communication delays.

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Chapter 3

Research Platform 1: MASnet Platform

3.1 Overview

The MASnet platform was developed at CSOIS, Utah State University, to conduct experiments on swarm engineering, like formation building, environmental monitoring as well as tracking. The initial purpose of this platform was to study diffusion processes and autonomous agent's abilities to track them. This platform consists of several robots called MASmotes, which act as wireless sensors and actuators, and have the capability of communicating with each other. In this research, the initial goal was to use this platform along with the MASmotes to develop platooning algorithms and test them for their performance requirements. Using these motes, a table top demonstration of vehicle platooning complete with merging and splitting capabilities was the initial focus of this research. A brief description of the platform is given in the next section.

3.2 Description of the MASnet Platform

The MASnet platform is made up of the following elements:

- 2.5 x 4 x 0.15 m Plexiglas surface with wooden supports,
- Sensor array (optional),
- Sensed element,
- Pseudo GPS (pGPS) camera,
- Base station computer,
- MicaZ motes.

The base station transmits commands wirelessly to the robots which execute them. The pGPS camera monitors robot position; this camera information is displayed on the base station. The base station calculates the desires positions and according to position error, sends commands to the robots. The robots receive these commands and move to the desired position. Thus, the whole system works as a feedback loop. Figure 3.1 shows an overview of the MASnet system as seen in the thesis by Rounds [5].

The robots are called MASmotes. They are built from relatively cheap, off-the-shelf, commercially available parts in order to build a low cost system. The robots' controller is the MicaZ mote from crossbow, as shown in Fig. 3.2.

This MicaZ 58 x 32 x 13 mm programming board is developed by Crossbow for communication, sensing, and computation of the individual robots. Specifications of this board are listed below:

- 8 MHz ATmega 128L main CPU;
- 128 KB programmable flash memory;
- 4KB EEPROM;
- 512KB flash memory;
- Changeable PWM outputs with eight 10-bit ADC channels;
- CC240 RF transceiver chip for wireless communication at 2.4GHz, with maximum communication rate of 250 kbps.

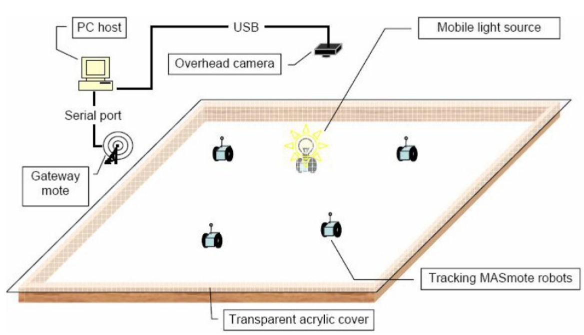


Fig. 3.1: Layout of the MASnet platform.

The mote is interfaced to the base station computer via a 51-pin connector. It operates on a 3V supply (2 AA batteries). It has 3 Led's for status display.

The MASmotes (Fig. 3.3) have gone through several upgrades in design. The current version, known as "gen2" motes (second generation), have the following components:

- 1 MicaZ programming board,
- 2 photodiodes,
- 2 IR sensors,
- 2 servos,
- 2 encoders,
- 1 unused sensor port.

3.3 Software Description

The MASnet platform requires two different softwares to function. The programming language for the robots is tinyOS and nesC. The base station runs a custom written program called the Robot Commander.

Fig. 3.2: MicaZ mote from Crossbow.

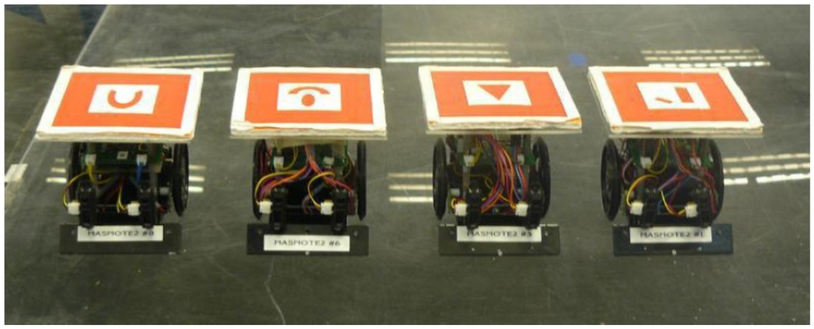


Fig. 3.3: MASnet robots with their markers attached to the top.

3.3.1 TinyOS and NesC

TinyOs is an event driven operating system developed by University of California, Berkeley and designed for WSN's with limited memory [138]. The tinyOS system is developed in nesC, which is similar to C. This programming language is used mostly for embedded systems such as the WSN on the MASnet platform. The language has been optimized for hardware sensor access with the support for interrupts and task management capabilities. This system is ideal for embedded projects due to its low memory and power requirements and the ability to multitask.

3.3.2 Robot Commander

The base station runs on a customized program called the Robot Commander. This is a program written in C++ and uses microsoft foundation classes (MFC). Details can be seen in the thesis by Burgeous [139]. The base station is programmed to read and process information coming from the base station mote or gateway mote (a gateway for communications between base station and MASmotes) and pGPS camera, and send commands through the gateway. This process is done via Robot Commander. A GUI of the Robot Commander is shown in Fig. 3.4.

The primary functions of the Robot Commander are listed below:

- Real time image processing

    1. Camera control and stream the video,

2. Capture and analysis of pGPS images,

3. Obtain MASnet platform position coordinates by transforming marker positions from pGPS images;

- Communication

  1. Receive messages from the MASmotes via the gateway mote,

  2. Send commands to MASmotes via the gateway mote;

- Data logging;

- Provides the GUI.

Using the pGPS images, Robot Commander finds the positions of the robots from the unique markers on top. Each robot has a unique marker assigned to it (Fig. 3.3). These markers are then detected by an ARToolkit, which detects the red frame first and then identifies the robot from the symbol. On identification of the robot, its unique ID, position and orientation information is logged and broadcasted to all other robots.

For a tutorial on how to set up the Robot Commander and get the system up and working, refer to the appendix of the thesis by Rounds [5].

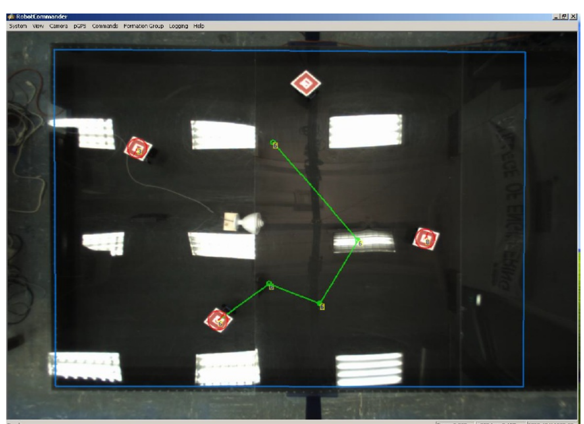


Fig. 3.4: Robot Commander GUI.

3.4 Issues Faced with the MASnet Platform

In this research, work started on the platform to develop vehicle platooning algorithms to show a table top demonstration of platooning. However, a lot of technical and hardware issues were faced. For descriptions of the different softwares, refer to Appendix A, and for a fix to compilation issues, refer to Appendix B. One of the main issues being faced was that the base station computer was really old and outdated and had loads of redundant data on it. Due to the work being done on the platform by students right from the year 2003 and there being modifications and additions to all the files, problems in locating the required files were being faced. Missing files, outdated versions of softwares like TinyOS, nesC, and missing Robot Commander files required the adoption of a new platform in the form of the LEGO mindstorm NXT 2.0. This platform is explained in the next chapter.

Chapter 4

Research Platform 2: LEGO Mindstorm NXT 2.0

4.1 Introduction

Due to the issues arising with the MASnet platform, a new platform was adopted which was the LEGO mindstorm NXT 2.0. The Lego mindstorms NXT robotics kit is a widely used platform in universities and research facilities. It is being used as a platform for implementing theoretical results and analyzing varied scenarios. The NXT is a programmable robotics toolkit, released by Lego in July 2006. The NXT came as a replacement for the "robotics invention system," a first generation Lego mindstorm kit. Legos are one of the most widely used platforms in many universities and research facilities. Being an affordable robotics toolkit that can do wonders, it has been used to implement and analyze both practical and theoretical results. In this research,the motivation behind using the NXT was to build a cheap and user friendly platform for verifying theoretical results from research on platooning, and demonstrate them on the NXT.

4.2 LEGO NXT Brick Description

Initially, a vehicle was built that had differential drive characteristics. Default programming of the brick is done in a graphical programming language that comes along with the kit, called NXT-G. However,by updating the firmware, the NXT can be programmed using a variety of languages like LabVIEW, Matlab Simulink, Java (leJOS NXJ), NXC, NBC, and RobotC, which is similar to C. The NXT Brick is the brain of the robot (Fig. 4.1).

The brick is the main component of the NXT. Specifications are listed below:

- 4 sensor inputs (1,2,3,4 as seen in Fig. 4.1),

- 3 motor inputs (A,B,C as seen in Fig. 4.1),

Fig. 4.1: LEGO NXT 2.0 intelligent brick.

- 100 x 60 pixel monochrome LCD display,
- 32-bit ARM processor,
- 256 KB flash memory,
- 64 KB RAM,
- 8-bit AVR microcontroller,
- Bluetooth connectivity,
- Powered by 6 AA batteries.

Lego has released an open source firmware for the NXT intelligent brick, hence making programming flexible and versatile. Simple default programs are present in the menu of the brick for beginners. Customized and more complicated code can be downloaded onto the brick either via USB cable, or bluetooth connectivity. Programs can also be shared between NXTs via bluetooth. The default programming language that comes bundled with NXT is the NXT-G. Real world programming can be done using NXT-G simply by construction of blocks and wiring them together. LeJOS NXJ is a high-level open-source language based on Java that uses custom firmware developed by the LeJOS team. MATLAB and Simulink are again high-level programming languages for computation, data acquisition, and analysis. Control of the LEGO NXT is obtained over a bluetooth serial port or USB connectivity.

Simulink is used for modeling and simulating dynamic systems. In Simulink, a backhand C code is generated. The code can be compiled and downloaded into the NXT brick.

4.3 Description of the Vehicle Designed Using NXT

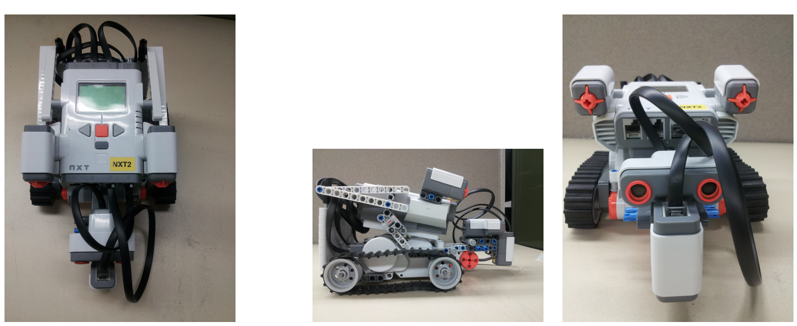
Initially, a differential drive vehicle model was developed, as shown in Fig. 4.2.

The vehicle had three motors connected to ports A, B, and C of the brick, an ultrasonic sensor mounted in the front to measure distances to the vehicle in front and a color sensor to perform the line following function.

4.4 Programming the NXT in LabVIEW

LabVIEW was used to develop the control algorithms for lateral (line following) and longitudinal (distance keeping) control. LabVIEW is a graphical programming language widely used in industries for data acquisition and analysis. It is a system design software which can be used to create and deploy measurement and control systems through unprecedented hardware integration [140]. In LabVIEW, the control system was implemented to demonstrate vehicle platooning as seen in Fig. 4.3.

The working of the program is explained here. A leader-follower implementation in LabVIEW uses ultrasonic sensors on the follower which measures the distance to the leader (in centimeters). The set point for the inter-vehicular distance is entered into the GUI as shown in Fig. 4.4.



(a) Top view. (b) Side view. (c) Front view.

Fig. 4.2: Overview of the designed vehicle.

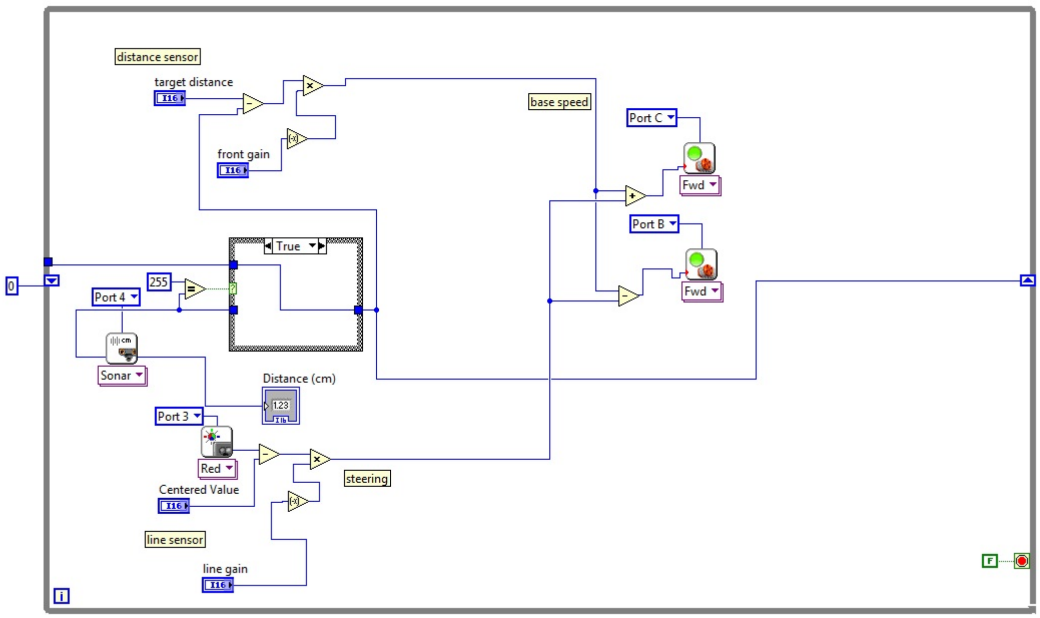


Fig. 4.3: Implementation of the code in LabVIEW.

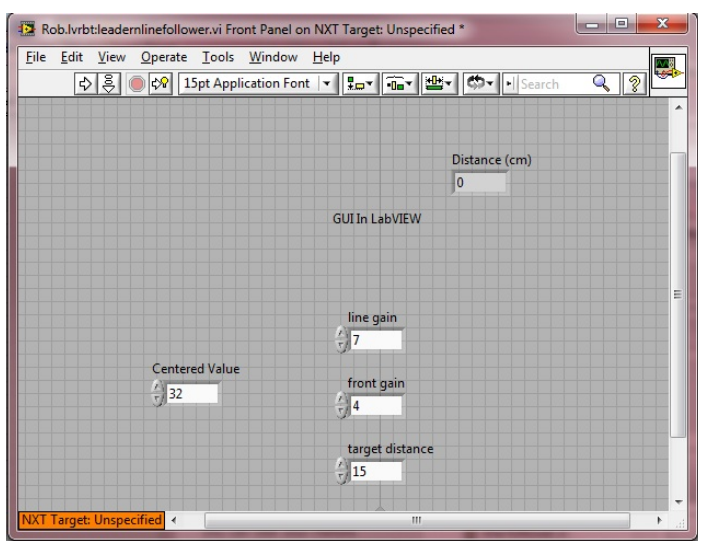


Fig. 4.4: Graphical user interface in LabVIEW.

A proportional controller maintains the distance between the vehicles as per the set point. The gains are set from the graphical user interface. Here, the gain for the longitudinal controller is 4 and that for the lateral controller is 7. Desired distance between vehicles is 15 cm. The working if longitudinal control is fairly simple. The ultrasonic sensor measures the distance to the vehicle in front. This value is compared with the desired set point. The error is then amplified by a gain of 4, to determine the power to be delivered to the motors. If the error is positive, meaning the measured distance is less than set point, then less power is delivered to the motors and the robot slows down to maintain the inter-vehicular spacing. If the error is negative, meaning the measured distance is more than set point, then the motors get more power and the vehicle speeds up. For the lateral control, a line following concept is implemented, which is similar to the lateral control implemented by PATH (using magnetic markers). The color sensor on the robot is used in the light sensing mode. The value obtained when the sensor is reading white and the value obtained when the sensor is reading black is averaged out. This average value is given as set point. In testing the sensor, the values obtained are shown in Table 4.1. Depending on what the color sensor reads, the robot turns to left or right. The power delivered to the motors depends is proportional to the turn needed. If the reading is 49, it means the sensor is reading white and the robot should turn right so more power is delivered to the right wheels as compared to left. Similarly, if reading is 17, it means robot needs to turn left and left wheels get more power. The ultrasonic sensor is noisy and when it does not get a good reading, it reads a default value of 255. This is filtered out in the code by adding some logic. When the sensor reads 255, the last used value in the loop is used. This is done by adding a shift register to the case structure. When the sensor gives a good reading, that reading is used instead of the last reading. This can be seen in Fig. 4.3. A modified version of the code is shown in

Table 4.1: Color sensor readings.

Sensor Reading for White	Sensor Reading for Black	Average Reading
49	17	33

Fig. 4.5. This version introduces bluetooth communication between the vehicles.

This code was better than the previous since in the previous code, if the leader vehicle stopped when facing an obstacle in its path, the follower would also stop at the predefined distance, but would continue to oscillate back and forth. This was overcome by introducing better logic into the code which brought the follower to a complete stop at the predefined distance. Also, due to lack of inter-vehicular communication, when going along a curved path, the follower came dangerously close to the leader due to the limitation of the ultrasonic sensor. This was solved by adding bluetooth communication between leader and followers. Here, if the leader starts tracing a curve, it sends a message to the followers, which reduces the velocity of the followers while maintaining safe inter-vehicular distances. As soon as the leader finishes tracing the curve and follows a straight path, the followers accelerate to catch up to the leader. The follower code is shown in Fig. 4.6.

When the follower receives a message from the leader, it stores it in its mailbox, and the logic shown is executed to reduce its velocity on turns. When the leader starts accelerating and the inter-vehicle spacing increases, the follower starts accelerating to minimize this gap. Emergency braking scenario is also demonstrated here. If the follower comes within a specified range of the leader, it is brought to an immediate halt to prevent collisions.

4.5 Programming the NXT in Simulink

Since modeling the motors was not possible in LabVIEW to perform experimental analysis on the LEGO and develop a controller for them, Simulink was used. Matlab version 2012a has developed a toolbox for the LEGO mindstorms NXT so that they can be interfaced with a computer to study the motor performances and similar characteristics. The vehicle design was modified to have Ackermann steering, to make it more like a real car. A PID controller was then designed for both speed and position control of the vehicle. In order to design the speed controller in Simulink, the motor model was derived by performing an open-loop step response test. The Simulink model in Fig. 4.7 shows the open-loop step response model.

The response obtained is shown in Fig. 4.8.

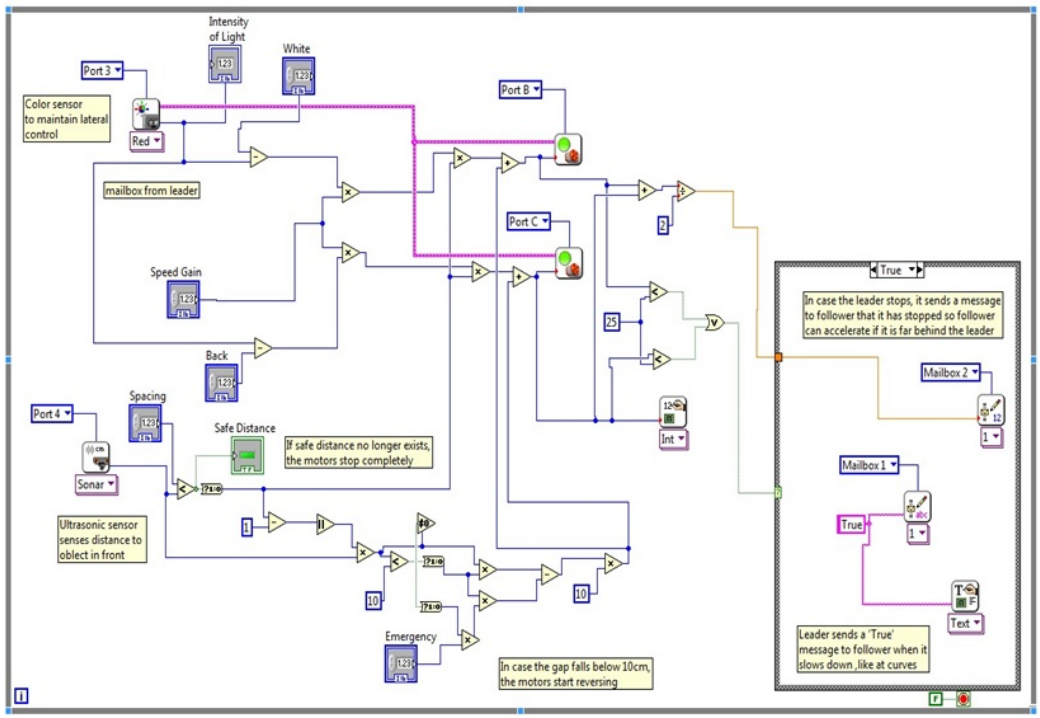


Fig. 4.5: LabVIEW code for the leader vehicle.

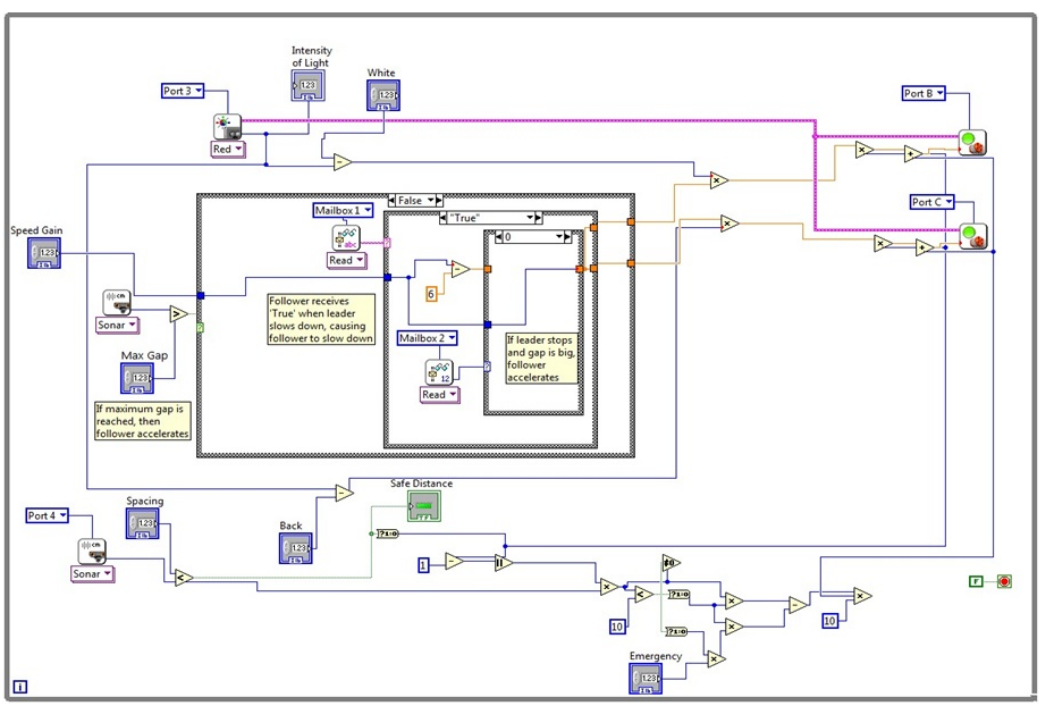


Fig. 4.6: LabVIEW code for the follower vehicle.

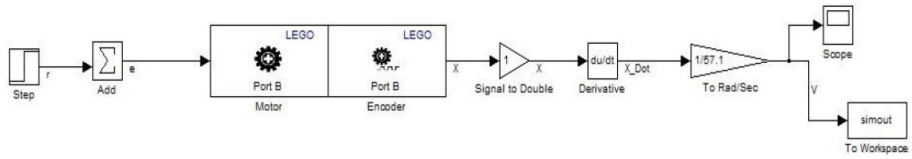


Fig. 4.7: Simulink block diagram for open-loop step response of NXT motor.

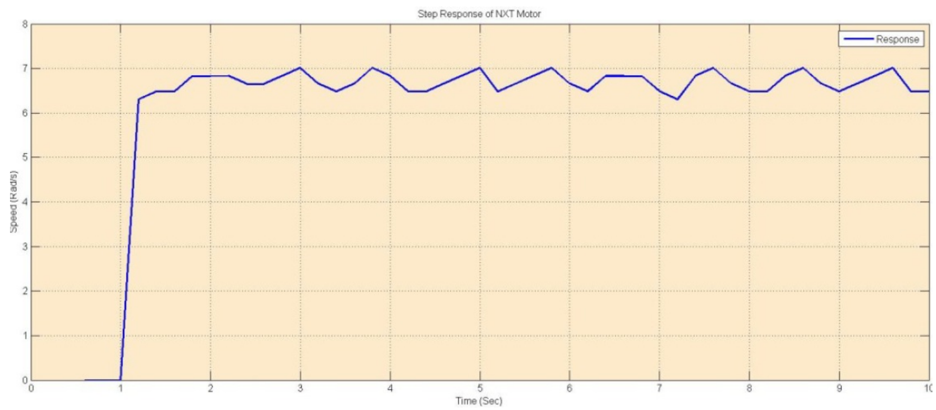


Fig. 4.8: Open-loop step response of motor.

This response is noisy since it is a speed response and hence involves taking the derivative of position. Introduction of derivative action leads to noise. A filter is used to eliminate noise. The motor model is given as

$$G(s) = \frac{K}{\tau s + 1}, \tag{4.1}$$

where τ is the motor time constant and K is the dc gain. From the response, the motor model is obtained as

$$G(s) = \frac{0.159}{0.125s + 1}. \tag{4.2}$$

Nonlinearities associated with the motors are saturation of the power ± 100 and a dead zone of $\pm 12\%$. The Simulink block diagram and the response obtained using this model is shown in Fig. 4.9.

The magnitude of the step is 50% of power. A comparison of simulated and experimental responses is shown in Fig. 4.10.

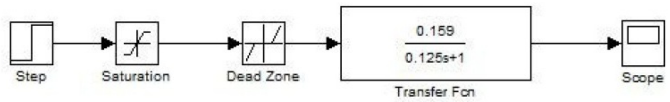


Fig. 4.9: Simulink model for open-loop step response of motor using model obtained.

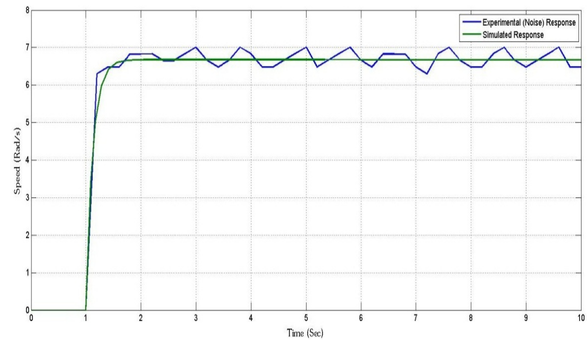


Fig. 4.10: Comparison of simulated and experimental responses.

4.6 PID Controller Design

The relay method was used to obtain the controller gains. The closed-loop system is shown in Fig. 4.11.

The responses obtained are shown in Fig. 4.12.

For the Relay Method, we need to obtain the parameters "H" and "A" as shown in Fig. 4.13.

These values are: $H = 50$, $A = 1.48$, and $P_u = 0.12$. Using Ziegler-Nichols tuning rules from Fig. 4.14, $K_{cu} = \frac{4h}{\pi A}$.

Using these rules, the PID controller was obtained as shown in Table 4.2.

Using these gains, the best response obtained is shown in Fig. 4.15.

After fine tuning the controller, the final PID gains obtained are shown in Table 4.3.

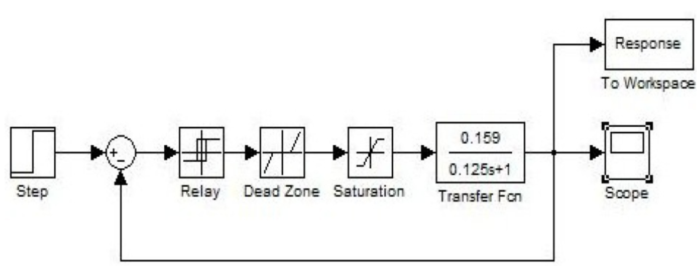


Fig. 4.11: Simulink diagram for the relay method.

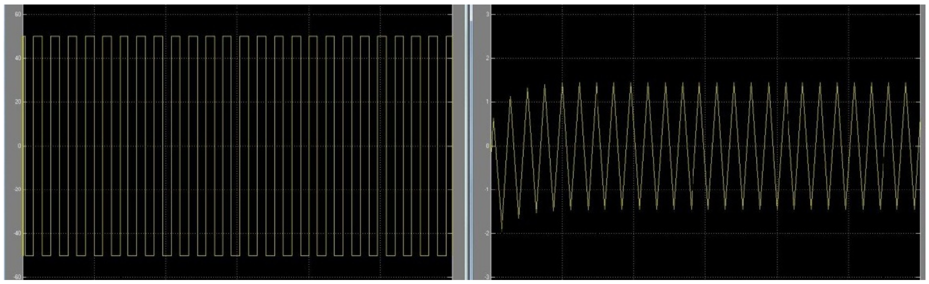


Fig. 4.12: Response from the relay method.

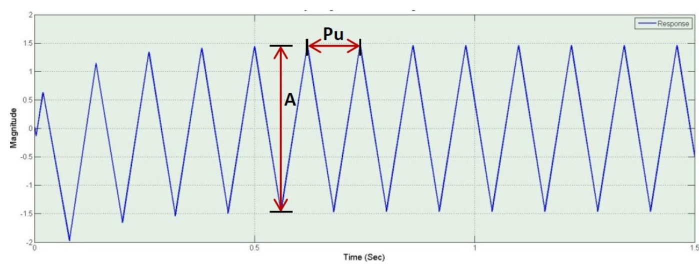


Fig. 4.13: Relay method.

	K_P	T_i	T_d
P	$0.5K_{cu}$		
PI	$0.45K_{cu}$	$P_u/1.2$	
PID	$0.6K_{cu}$	$P_u/2$	$P_u/8$

Fig. 4.14: Ziegler-Nichols tuning rules.

Table 4.2: PID controller design for speed.

K_p	K_i	K_d
25.8	430.15	0.3871

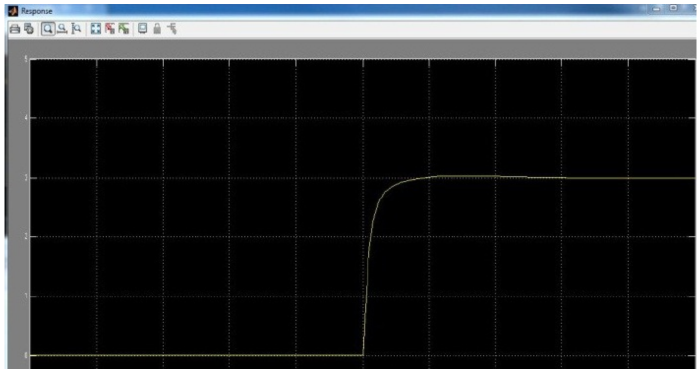


Fig. 4.15: Step response using obtained PID gains.

Table 4.3: Gains obtained on tuning.

K_p	K_i	K_d
25.8	400	1.5

The controller hence obtained is shown in Eq. (4.3).

$$25.8 + \frac{400}{s} + 1.5s \tag{4.3}$$

This controller was implemented on the NXT but an overshoot of about 12.5% was obtained. To remove this overshoot, anti-windup was implemented as shown in Fig. 4.16.

The response obtained is shown in Fig. 4.17. The PID gains are shown in Table 4.4

It has 0% overshoot.

The controller obtained was stable and robust. Response to set point changes and disturbances (Fig. 4.18) proved this controller design to be robust.

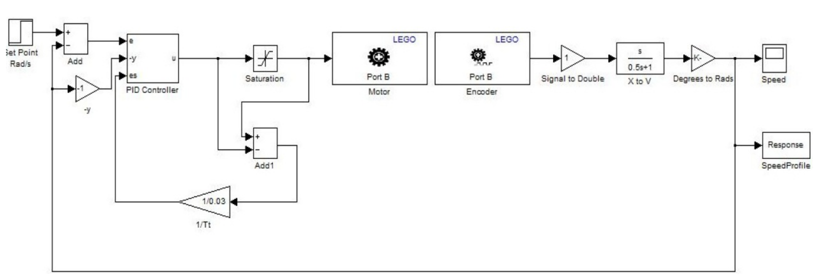


Fig. 4.16: PID with antiwindup.

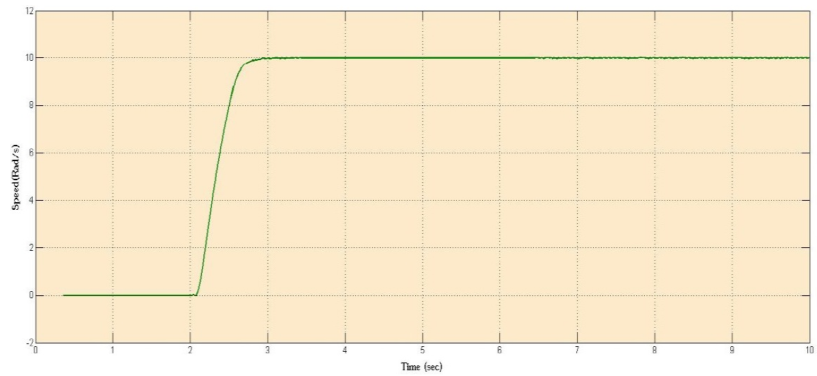


Fig. 4.17: Step response for PID with antiwindup.

Table 4.4: PID controller design for speed with antiwindup.

K_p	K_i	K_d
100	600	1

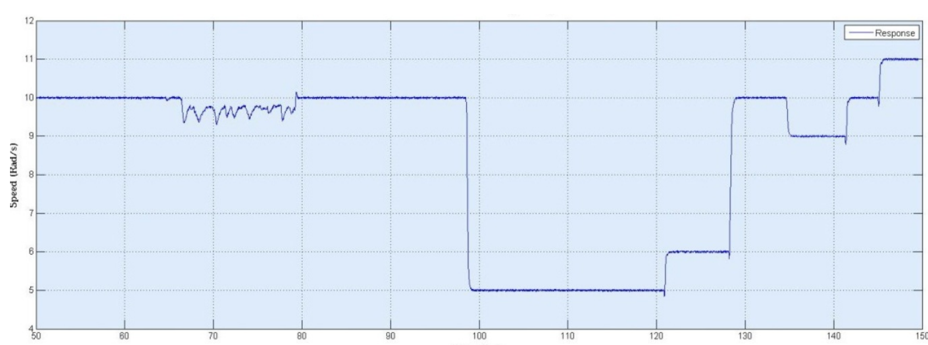


Fig. 4.18: Response to set point changes and disturbances.

4.7 Position Controller Design

Similar methods were used to design the position controller. However, instead of the relay method, the critical gain method was used. The model obtained was

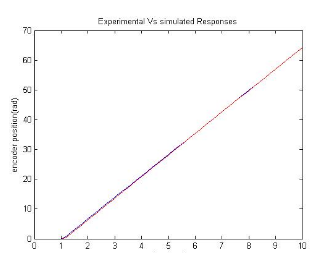
$$G(s) = \frac{0.181}{0.125s^2 + s}. \tag{4.4}$$

A comparison plot of simulated vs experimental data is shown in Fig. 4.19(a). The critical gain and period of oscillations was obtained from Fig. 4.19(b) as $K_{cu} = 170$,$P_u = 0.8$.

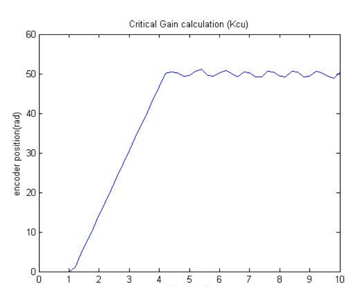
By using the Ziegler-Nichols tuning rule from Fig. 4.14, the PID gains were obtained as shown in Table 4.5. The Simulink block diagram for position controller with anti-reset windup can be seen in Fig. 4.20.

The controller obtained was found to be stable and robust to disturbances (Fig. 4.21) and set point changes (Fig. 4.22).

The final Simulink block diagram for position and speed controller can be seen in Fig. 4.23.



(a) Comparison of simulated and experimental responses.



(b) Response obtained when gain is critical gain K_{cu}.

Fig. 4.19: Simulated and experimental response comparison and critical gain response.

Table 4.5: PID controller design for position.

K_p	K_i	K_d
102	10.2	255

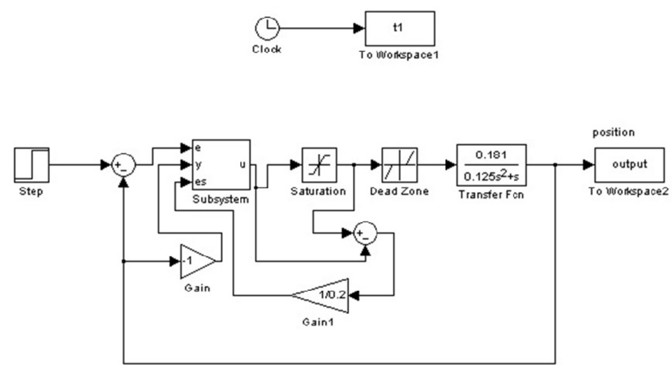


Fig. 4.20: Simulink block diagram for position control system.

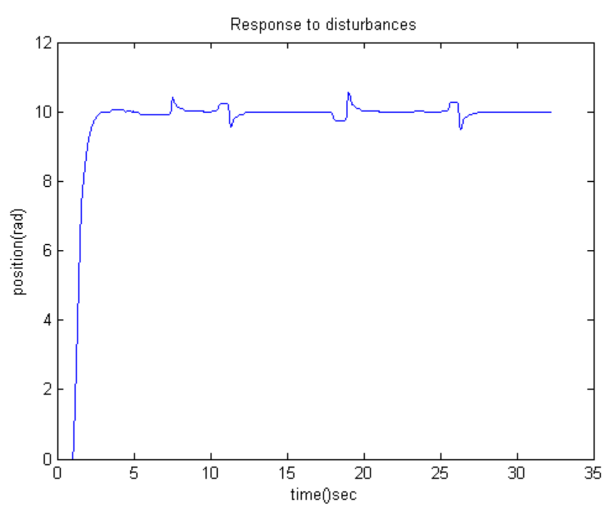


Fig. 4.21: Responses to disturbances.

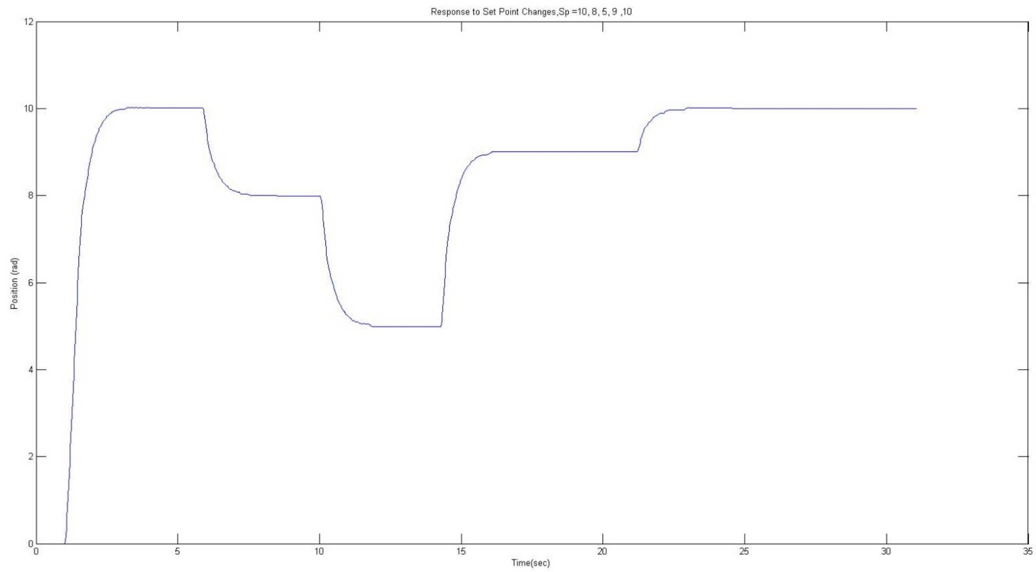


Fig. 4.22: Responses to set point changes.

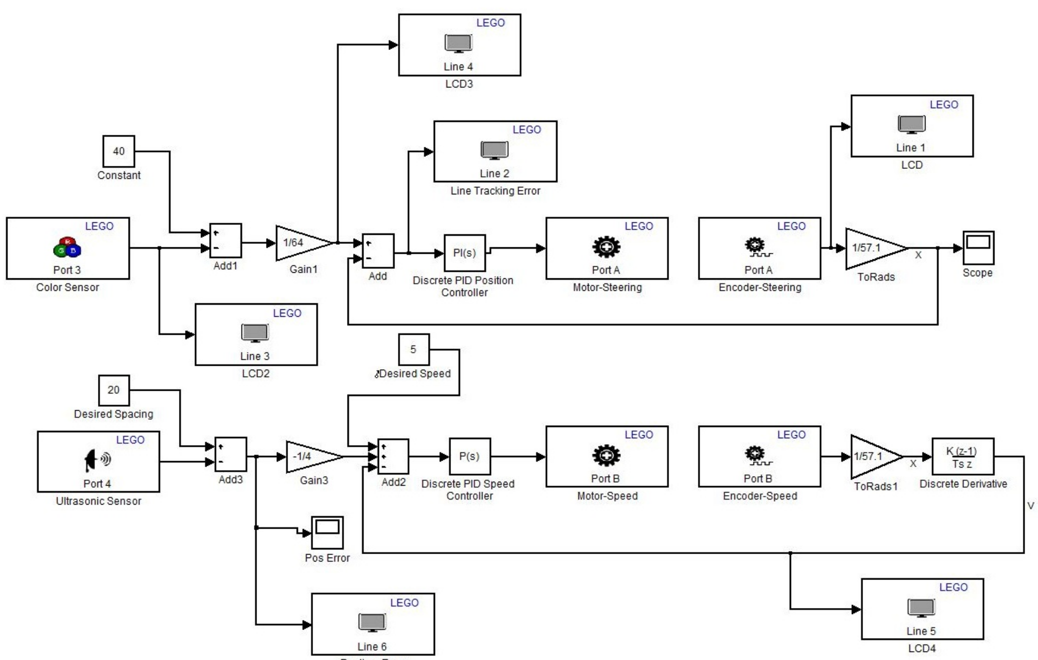


Fig. 4.23: Speed and position control.

Chapter 5

Analysis of Control Strategies for Cognitive Vehicle Platooning

Several control strategies have been proposed in literature for both lateral and longitudinal control of a platoon of vehicles. The word "cognition" means the "mental process of knowing, including awareness, perception, reasoning and judgement" [141]. This thesis analyzes a few control strategies and their influence on parameters such as inter-vehicular spacing, robustness of control design and stability of control design. In the next few sections, algorithms based on distance-based platoon control and position-based platoon control is analyzed and their differences are enlisted. A few other strategies are are also defined.

5.1 Cognitive Vehicle Platooning Control

Vehicle platooning control is a type of formation maintainence and control through cooperation between the platoon members. This cooperation is nothing but IVC. A cooperative control system consists of multiple autonomous agents having the ability to sense and communicate with each other. If only local information is available to the group, then using this information, predefined agent and group behaviors is achieved via the sensing and communication devices.

Topology of information flow is important in cooperative control. In platoon formation control, the main target is to stabilize the relative positions or distances between platoon members to desired values.

Topology of information exchange between the agents is represented by graph theory. If agent i can access the information of agent j, then it is said that agent j is the neighbor of agent i. The information flow between agents is then represented by a graph, wherein each agent is a "node" and flow of information between nodes is represented by "links." Group objectives are achieved by the use of distributed laws, which use only local information.

5.2 Cooperative Control Using Passivity-Based Design

Cooperative control problems can be targeted using the passivity-based design, as analyzed by Bai et al. [142]. There are certain advantages of the passivity-based approach as compared to conventional approaches. These are listed below:

- Design possible for higher order agent dynamics;
- Robust behavior, flexibility of design, and adaptivity;
- Ease of modularity and scalability.

The passivity-based design assumes bidirectional communication topology. This means that both agents communicate with each other. This type of topology has shown to guarantee stability by Bai et al. [142].

The definition of passivity and its relation to stability is given by Bai et al. [142] as follows.

Passivity of Static Nonlinearity:

A static nonlinearity $y = h(u)$, where $h : \mathbb{R}^p \to \mathbb{R}^p$, is *passive*, if, $\forall u, \in \mathbb{R}^p$

$$u^T y = u^T h(u) \geq 0, \tag{5.1}$$

and strictly passive if Eq. (5.1) holds with strict inequality $\forall u \neq 0$.

Passivity and Strict Passivity of Dynamical Systems:

The dynamical system as shown in Eq. (5.2)

$$H = \begin{cases} \dot{\xi} = f(\xi, u) \\ y = h(\xi, u) \quad \xi \in \mathbb{R}^n, u, y \in \mathbb{R}^p, \end{cases} \tag{5.2}$$

is passive if there exists a C^1 storage function $S(\xi) \geq 0$ such that Eq. (5.3) holds true

$$\dot{S} = \Delta S(\xi)^T f(\xi, u) \leq -W(\xi) + u^T y, \tag{5.3}$$

for some positive semi-definite function $W(\xi)$. Eq. (5.2) is strictly passive if $W(\xi)$ is positive definite.

Strict Input and Output Passivity:

For the dynamic system Eq. (5.2), if S in Eq. (5.3) satisfies Eq. (5.4)

$$\dot{S} \leq -u^T \psi(u) + u^T y, \tag{5.4}$$

for some function $\psi(u)$ such that $u^T \psi(u) > 0$, then Eq. (5.2) is input strictly passive. If Eq. (5.5) holds for some function $\psi(y)$ where $y^T \psi(y) > 0$, Eq. (5.2) is output strictly passive

$$\dot{S} \leq -y^T \psi(y) + u^T y. \tag{5.5}$$

Cooperative Control Using Passivity-Based Design

An important consideration when designing controllers for platoon formation control is the stability of the formation. If only local information is available, it is possible to design feedback laws to solve the problem of stability. A key assumption however, is bidirectional communication. Control objective is mainly to bring the differences between the output variables of all the members of the platoon to some specific values in the form of a compact set. These output variables could be relative velocities, positions, or accelerations. When these output variables are positions of the platoon members that need to maintain fixed inter-vehicular distances, the compact set results in a sphere. If the output variable is velocity, then this becomes an agreement or consensus problem. In this case, the compact set is the origin, since we want to steer the velocities of all the platoon members to the leader velocity. Hence, the ultimate goal is to achieve stability for this compact set. A stabilizing feedback law can hence be constructed using passivity-based design techniques. Using additional assumptions detailed by Bai et al. [142], global asymptotic stability can also be proved.

5.3 Problem Definition

Consider a platoon of N agents. The variables that need to be coordinated with the rest of the members can be represented by a vector $x_i \in \mathbb{R}^p$, where $i = 1, ..., N$. Information flow between the agents is represented as a graph "G," which is said to be an "undirected" graph due to the assumption of bidirectional information flow. "G" has "l" undirected links. Since agents are represented as nodes, one of the agents is considered to be a positive end of the link, for simplicity. Since information flow is bidirectional and symmetric, it does not matter which node is selected as positive end.

The ultimate objective is to attain limit in Eq. (5.6).

$$\lim_{t \to \infty} |\dot{x_i} - v(t)| = 0, i = 1, ..., N \tag{5.6}$$

Meaning, in the limit, the velocity vector of each platoon member $v(t) \in \mathbb{R}^p$ is equal to the leader velocity, and Eq. (5.7),

$$z_k = \sum_{l=1}^{N} d_{ik} x_l = \begin{cases} x_i - x_j & if, k \in L_i^+; \\ x_j - x_i & if, k \in L_i^-, \end{cases} \tag{5.7}$$

converges to a prescribed compact set $A_k \subset \mathbb{R}^p, k = 1, ..., l$. Here, d_{ik} is the "graph incidence matrix" given in Eq. (5.8)

$$d_{ik} = \begin{cases} +1 & if, k \in L_i^+; \\ -1 & if, k \in L_i^-; \\ 0 & otherwise. \end{cases} \tag{5.8}$$

L_i is the "graph Laplacian matrix"given in Eq. (5.9),

$$l_{ij} = \begin{cases} |N_i| & if, i = j; \\ -1 & if, j \in N_i; \\ 0 & otherwise. \end{cases} \tag{5.9}$$

N_i is the number of neighbors of agent i, z_k is the relative position between agents. There are two steps involved with the passivity-based design procedure.

Step 1: The dynamics of each agent $i = 1, ..., N$ is rendered passive from an external feedback signal u_i to the velocity error $y_i = \dot{x}_i - v(t)$ by designing an "internal" feedback loop.

Step 2: An external feedback system is designed which is given in Eq. (5.10),

$$u_i = \sum_{k=1}^{l} d_{ik}\psi_k(z_k), \tag{5.10}$$

where z_k is as in Eq. (5.7), and ψ_k are the nonlinearities, to be designed such that A_k's are asymptotically stable and invariant. For design of ψ_k, refer to the book by Bai et al. [142].

5.4 Position-Based Platoon Formation Control

In platoon formation control, a key consideration is formation stability and maintenance. This means steering the relative positions (z_k's) or relative inter-vehicular distances to prescribed values. Based on the goal, there are two concepts.

- Distance-based formation control, in which the desired target set A_k is given as $A_k = (z_k, |z_k| = d_k)$, $d_k \in \mathbb{R}_{>0}, k = 1, ..., l$.

- Position-based formation control, in which the desired target set A_k is given as $A_k = (z_k, z_k = z_k^d)$, $z_k^d \in \mathbb{R}^p, k = 1, ..., l$.

Differences between these two control strategies are listed later in the chapter. Simulation results and analysis for position-based control are presented in the following few paragraphs.

Consider the group members of the platoon have double integrator dynamics in Eq. (5.11),

$$m_i\ddot{x}_i = \tau_i, i = 1, ..., N, \tag{5.11}$$

where m_i is the mass of the agents, $x_i \in \mathbb{R}^p$ is the position vector of agent i, and $\tau_i \in \mathbb{R}^p$ is the force input. Referring back to *Step 1*, we have an internal feedback law given by Eq. (5.12),

$$\tau_i = -k_i(\dot{x} - v(t)) + m_i \dot{v}(t) + u_i, k_i > 0. \tag{5.12}$$

Next, applying *Step 2*, an external feedback law is designed in Eq. (5.13) as

$$u_i = -\sum_{i=1}^{l} d_{ik} \psi_k (z_k - z_k^d). \tag{5.13}$$

The overall closed-loop system can be seen in Eq. (5.14) as

$$m_i(\ddot{x}_i - \dot{v}(t)) + k_i(\dot{x}_i - v(t)) + \sum_{k=1}^{l} d_{ik} \psi_k (z_k - z_k^d) = 0. \tag{5.14}$$

Simulink model and simulation results of the position-based control system Eq. (5.14) are shown in Fig. 5.1 and Fig. 5.2, respectively.

From simulation results, it can be seen that position-based formation controller achieves stability of both shape and orientation. If only the shape of the formation is of concern, the distance-based formation control is used.

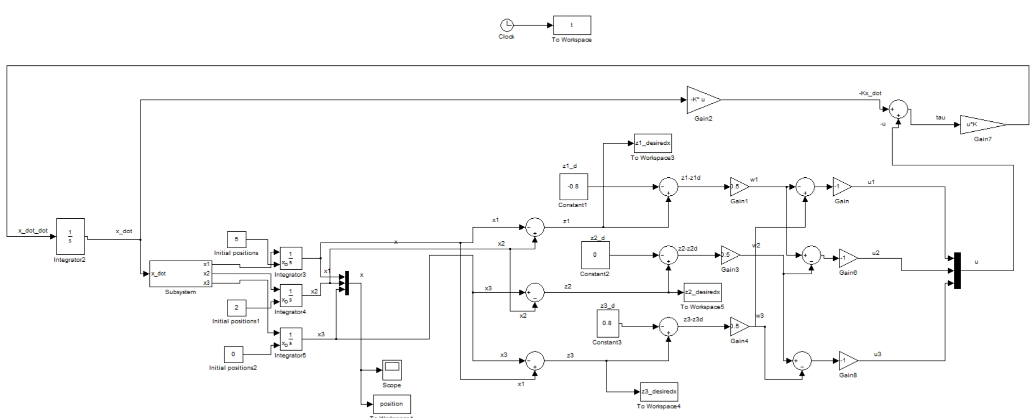
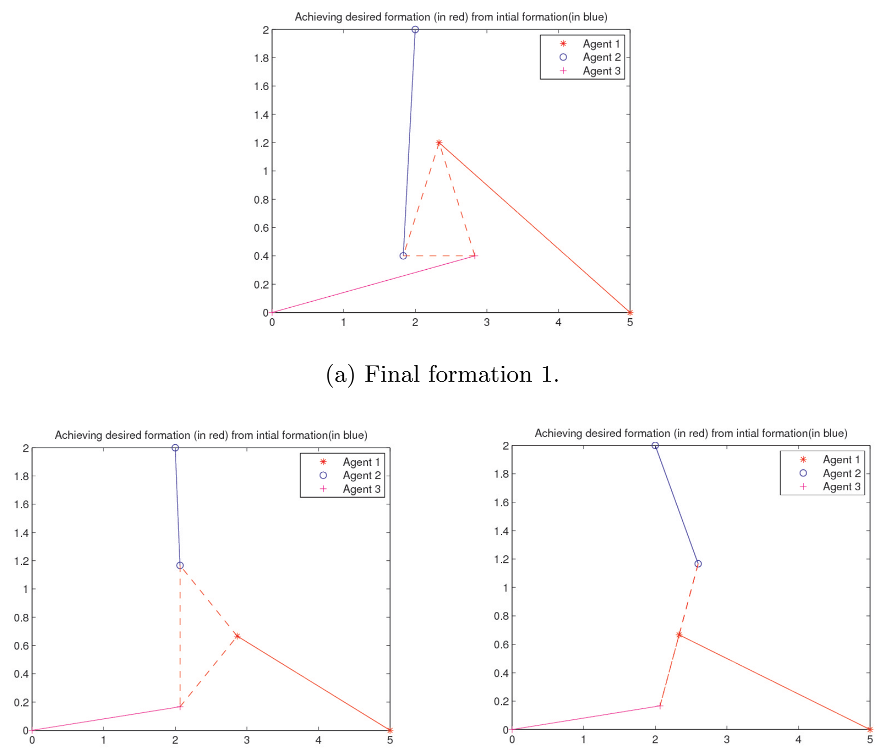


Fig. 5.1: Implementation of the position-based controller in Simulink.



(a) Final formation 1.

(b) Final formation 2.

(c) Final formation 3 (Platoon).

Fig. 5.2: Formation control using position-based controller.

5.5 Distance-Based Platoon Formation Control

The distance-based formation control problem is defined in Eq. (5.15).

$$A_k = (z_k, |z_k| = d_k), d_k \in \mathbb{R}_{>0}, k = 1, ..., l \tag{5.15}$$

Design of the distance-based formation controller is slightly different from that of the position-based controller. *Step 1* remains the same as defined previously for position-based control. In *Step 2*, the nonlinearities ψ_k are as designed by Bai et al. [142]. Here, d_k, which is the distance between agents, is set to 1. Simulink model and simulation results are shown in Fig. 5.3 and Fig. 5.4, respectively. The position variation of agents over time can be seen in Fig. 5.5.

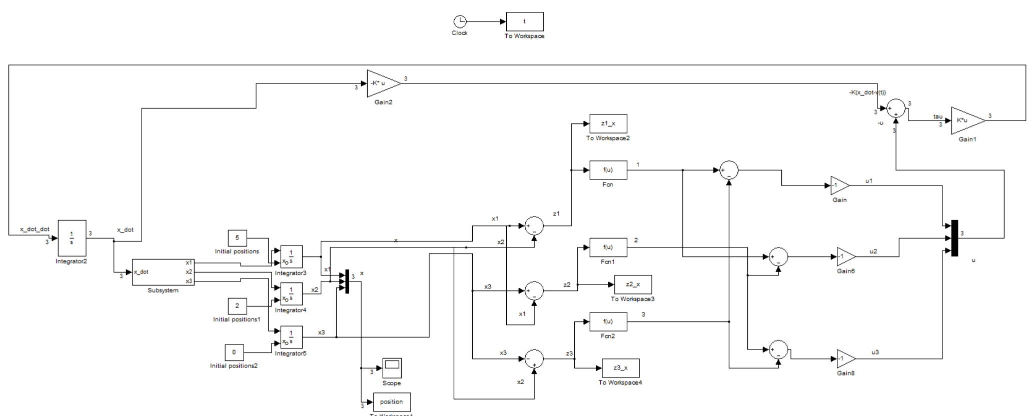
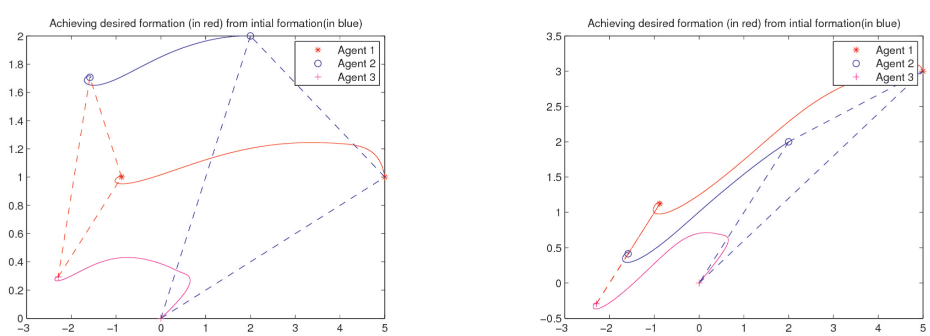
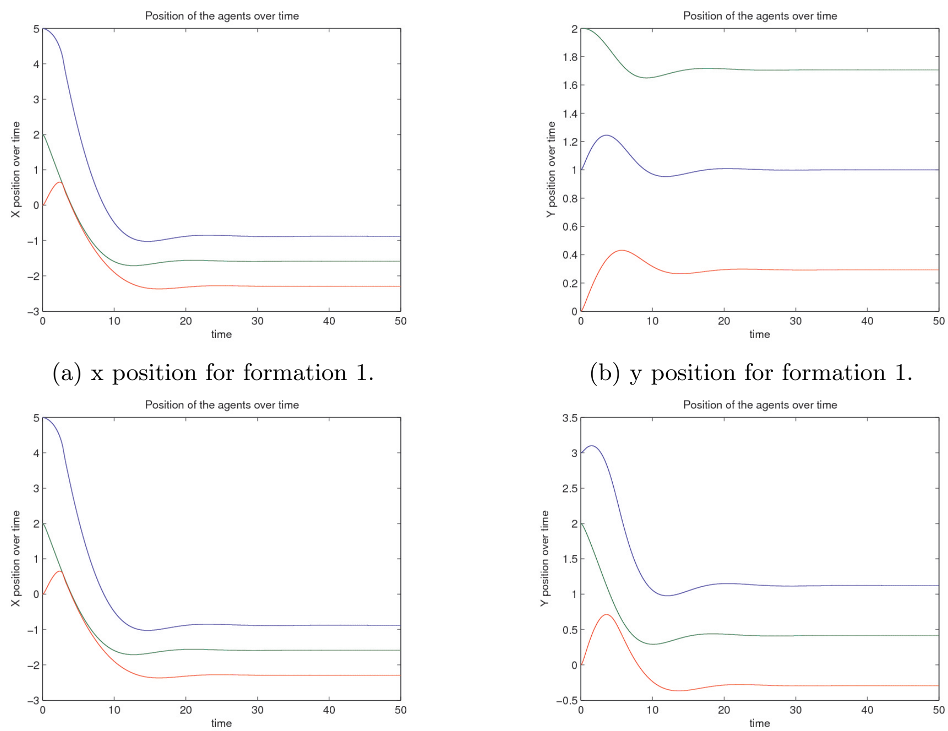


Fig. 5.3: Implementation of the distance-based controller in Simulink.



(a) Final formation 1. (b) Final formation 2 (platoon).

Fig. 5.4: Formation control using distance-based controller and zero reference velocity.



(a) x position for formation 1.

(b) y position for formation 1.

(c) x position for formation 2.

(d) y position for formation 2.

Fig. 5.5: Positions of the agents for Fig. 5.4.

Simulations results when a reference velocity of [0.1,0.1] is added are given in Fig. 5.6. Distances of the agents over time can be seen in Fig. 5.7.

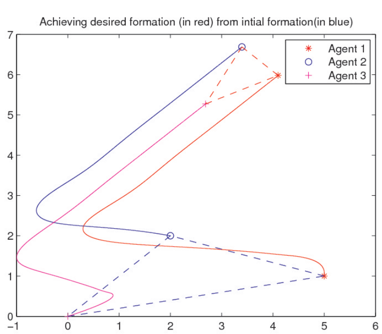
From these simulations results, it can be seen that the distance between the agents reached the desired distance of 1 meter specified in simulations. The controllers are robust in design and stable to disturbances as well. We can summarize the differences between distance-based and position-based formation control as follows.

- Equilibria

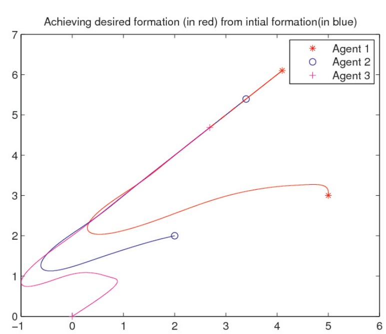
  The desired equilibria are seen to be spheres for distance-based control whereas for position-based control, these equilibria are nothing but a single point. So, the position-based control is important when both shape and orientation of the formation needs to be maintained. On the other hand, distance-based control is important only when the shape of the formation is to be maintained.

- Control design and flexibility

  Distance-based formation control requires the use of nonlinear potential functions, whereas position-based control can be implemented just by linear feedback laws. Distance-based control achieves stability only locally when the communication graph contains cycles, whereas position-based control is able to stabilize the formation globally.

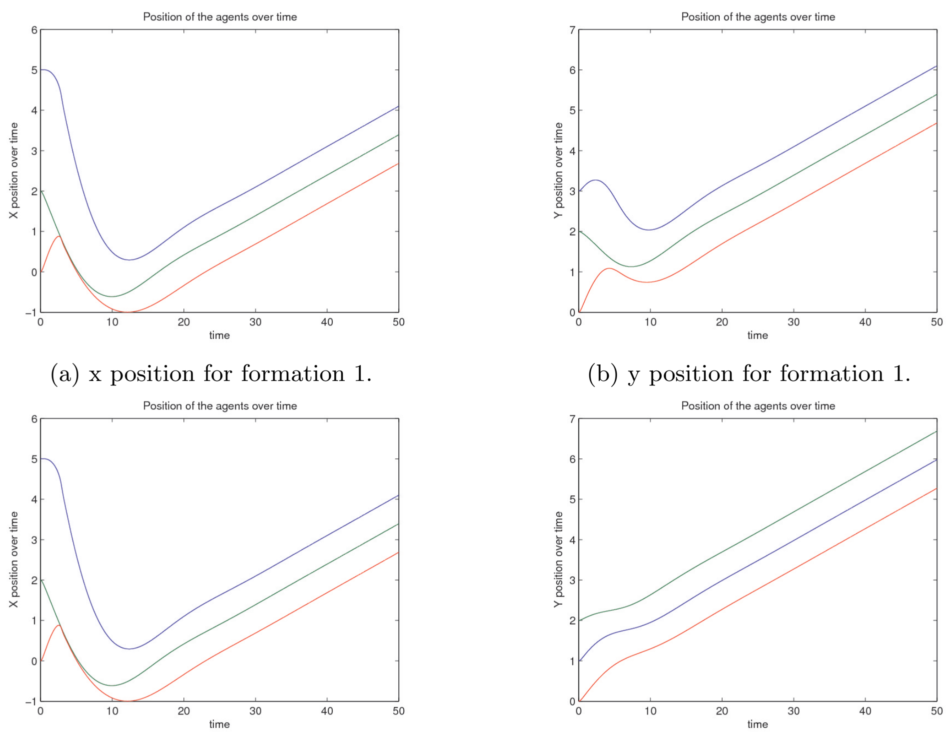


(a) Final formation 1.



(b) Final formation 2 (platoon).

Fig. 5.6: Formation control using distance-based controller and nonzero reference velocity.



(a) x position for formation 1.

(b) y position for formation 1.

(c) x position for formation 2.

(d) y position for formation 2.

Fig. 5.7: Positions of the agents for Fig. 5.6.

- Control law implementation

  Difference between control design is seen in Eq. (5.16) and Eq. (5.17).

$$Position - Based : \ddot{x}_i = \tau_i = -K_i\dot{x}_i - \sum_{k=1}^{l} d_{ik}(z_k - z_k^d) \tag{5.16}$$

$$Distance - Based : \ddot{x}_i = \tau_i = -K_i\dot{x}_i - \sum_{k=1}^{l} d_{ik}log(\frac{|z_k|}{d_k})\frac{1}{|z_k|}z_k \tag{5.17}$$

Distance-based control is used when no global information about the platoon is available.

5.6 Impedance-Based Control of a Platoon

Another widely used concept in vehicle platooning control is the use of spring damper system to model the interactions of vehicles with each other within a platoon as well as with the environment. Such a concept is described by Yi and Chong [143]. Utilization of a series of spring damper systems for the impedance control of a platoon is a well studied subject. Robustness of the controller designed to parametric uncertainties, model errors and noise in sensor measurements should be guaranteed to have safe platooning. Developing a guidance model and then incorporating vehicle dynamics to follow this guidance model is studied by Yi and Chong [143]. Since this impedance model consisting of spring damper systems is stable even to uncertain environments, it is widely used to model such interactions. An example of a guidance model is seen in Fig. 5.8.

In this model, global communication between platoon members is possible via wireless communications. All the vehicles are supplied with leader vehicle velocity, position, and acceleration information. Also, every vehicle has access to the preceding vehicle's position and velocity data. This type of communication topology has been proved to be string stable. However, in cases where a global communication link is absent, local interactions have to be used to achieve platoon control. Using this communication topology helps counter problems associated with global communication such as communication delays and packet drops. This uses a model as shown in Fig. 5.9.

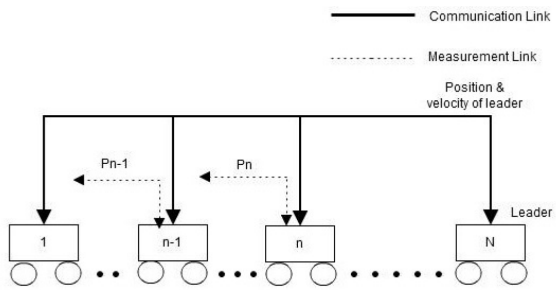


Fig. 5.8: Guidance model using global communication.

Finally, when no local or global communication is available, the spring damper impedance model is used to model interactions between vehicles. This model is shown in Fig. 5.10.

In this case, the position and velocity of the vehicle is found from subtracting the preceding vehicle's position and velocity from its own. When this guidance model is coupled with vehicle dynamics, complete platoon control is possible. This includes both lateral and longitudinal control. Incorporating this model, proposed by Yi and Chong [143], with vehicle dynamics, and using exiting methods for feedback linearization, provides a unified controller for lateral and longitudinal control.

5.6.1 Impedance Model for a Vehicle Platoon

Using spring damper system to demonstrate the interactions between vehicles,the forces between vehicles are given by Yi and Chong [143] as in Eq. (5.18),

$$f_f = k(p_{n+1} - p_n - d_n) + c(\dot{p_{n+1}} - \dot{p_n}), \tag{5.18}$$

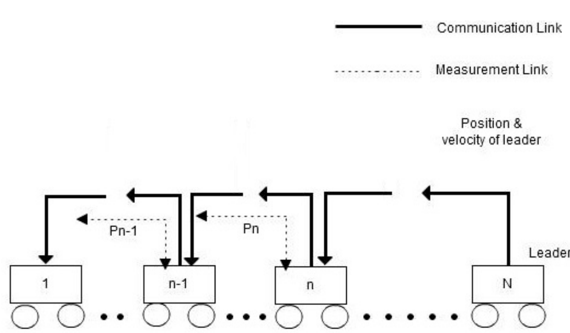


Fig. 5.9: Model using local communication.

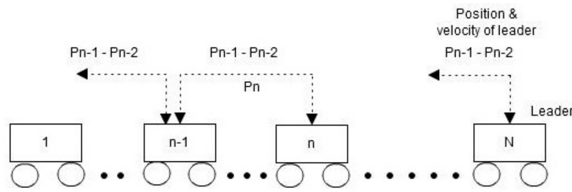


Fig. 5.10: Model without local communication.

which is the force between the vehicle 'n' and vehicle 'n+1'. Here, 'k' is the spring coefficient, 'c' is the damper coefficient, 'p_n' is the position of n^{th} vehicle, and '$\dot{p_n}$' is the velocity of n^{th} vehicle, and f_r is shown in Eq. (5.19).

$$f_r = k(p_n - p_{n-1} - d_{n-1}) + c(\dot{p_n} - \dot{p_{n-1}}) \tag{5.19}$$

Here, $d_n = d \cdot \frac{p_{n+1} - p_n}{\|p_{n+1} - p_n\|}$ is the inter-vehicular distance, $d > 0$. If the vehicle mass is 'm', 'N' is the total number of vehicles in the platoon, then the vehicle equation of motion can be written as in Eq. (5.20).

$$m\ddot{p_n} = f_f - f_r \tag{5.20}$$

$f_f = 0$ for lead vehicle, and $f_r = 0$ for last vehicle in platoon. Combining Eq. (5.18), Eq. (5.19), and Eq. (5.20), the controller equations proposed by Yi and Chong [143] are given in Eq. (5.21) as

$$\ddot{p_n} = \begin{cases} \frac{k}{m}(p_2 - p_1 - d_1) + \frac{c}{m}(\dot{p_2} - \dot{p_1}) & n = 1; \\ \frac{k}{m}(p_{n+1} - p_n - d_n) - \frac{k}{m}(p_n - p_{n-1} - d_{n-1}) & \\ + \frac{c}{m}(\dot{p_{n+1}} - \dot{p_n}) - \frac{c}{m}(\dot{p_n} - \dot{p_{n-1}}) & 2 \le n \le N-1; \\ \frac{-k}{m}(p_N - p_{N-1} - d_{N-1}) - \frac{c}{m}(\dot{p_N} - \dot{p_{N-1}}) & n = N. \end{cases} \tag{5.21}$$

5.6.2 Simulation Results

The controller in Eq. (5.21) was implemented in Simulink (Fig. 5.11).

Simulation results are presented. The leader vehicle trajectory is generated as shown in Fig. 5.12(a) and heading are shown in Fig. 5.12(b).

Platoon trajectory and inter-vehicular spacing for a reference of 5 meters and arbitrary initial positions is shown in Fig. 5.13.

It can be seen from the simulation results that the platoon follows the leader trajectory pretty well. The controller design is robust towards errors in model and other parametric uncertainties. It also leads to stable platoon behavior. Due to the impedance model, the error in inter-vehicular spacings gets damped out as the number of platoon members increases, ensuring that spacing errors do not propagate down a platoon, thus ensuring string stability. Thus, it can be concluded that stable platoon control can be achieved through the use of impedance model.

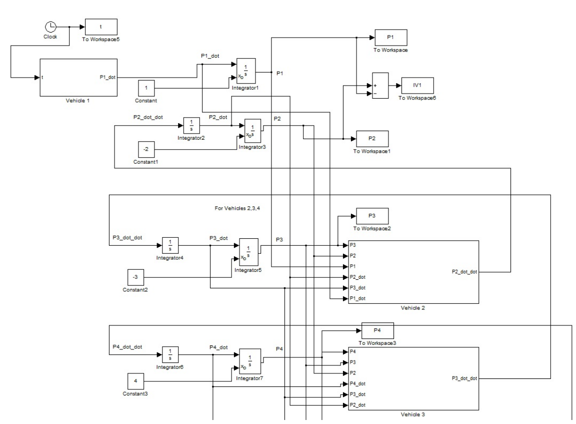
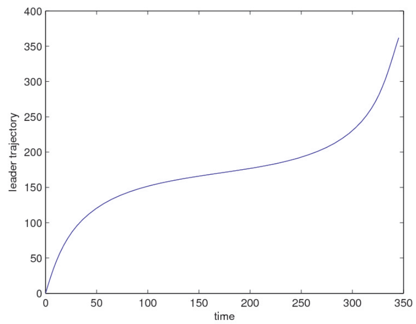
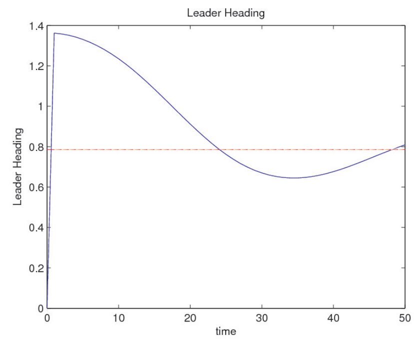


Fig. 5.11: Impedance model implementation in Simulink.

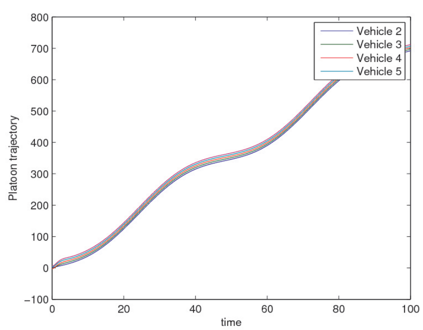


(a) Trajectory of the leader.

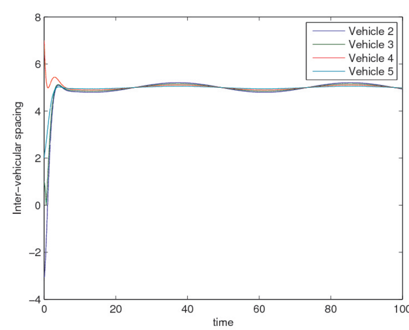


(b) Heading of the leader.

Fig. 5.12: Leader vehicle trajectory and heading.



(a) Platoon trajectory.



(b) Inter-vehicular spacings variation.

Fig. 5.13: Simulation results for platoon trajectory and inter-vehicular distances.

Chapter 6
Design of Fractional Order Controller for Optimal Vehicle Platooning

In this chapter, a fractional order controller for optimal vehicle platooning is designed, using passivity-based design technique. By minimizing the integral square error (ISE) in Eq. (6.1) of the position error signal, the order of the fractional controller is determined. Use of fractional calculus in history is well known for mathematical purposes. However, utilization of fractional calculus in controls is now an emerging researched topic. It has been shown by Bhambhani et al., Luo and Chen [144, 145] that fractional control can achieve much improvement in performance over integer order controllers. Techniques for tuning the fractional order controllers have been already been designed by Monje et al. [146]. This chapter analyzes the use of passivity-based control methods to achieve formations. ISE is given in Eq. (6.1),

$$ISE = \int_0^t (e_1^2 + e_2^2 + e_3^2)dt, \tag{6.1}$$

where e_1, e_2, and e_3 are the position errors of vehicle 1, 2, and 3, and t is the simulation time.

6.1 Fixing Optimal Gain K for Fractional Controller

Using the same passivity-based design steps discussed in Chapter 5 and shown below, simulations were run to determine optimal gain K in Eq. (6.2), for fractional order. Results showed that minimum ISE occurred at $K = 1$.

Step 1: The dynamics of each agent $i = 1, ..., N$ is rendered passive from an external feedback signal u_i to the velocity error $y_i = \dot{x}_i - v(t)$ by designing an "internal" feedback loop.

Step 2: An external feedback system is designed which is given in Eq. (6.2),

$$u_i = \sum_{k=1}^{l} d_{ik} \psi_k(z_k), \tag{6.2}$$

where z_k is as as discussed in previous chapter, and ψ_k are the nonlinearities, to be designed such that A_k's are asymptotically stable and invariant. For design of ψ_k, refer to the works of Bai et al. [142].

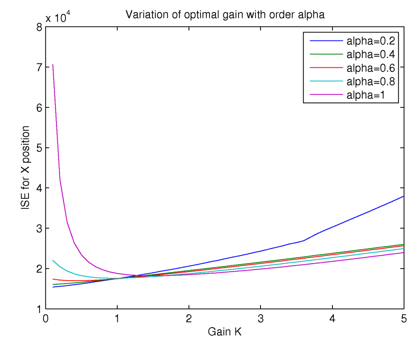
The optimal gain K varies with fractional order 'α' of the controller. This variation for X and Y positions can be seen in Fig. 6.1(a) and Fig. 6.1(b), respectively.

Simulation results showing the variation of ISE with controller order α for both x position and y position can be seen in Fig. 6.2(a) and Fig. 6.2(b), respectively.

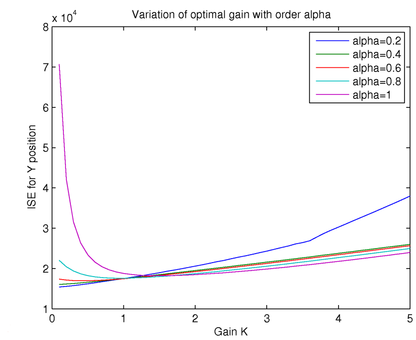
6.2 Comparison of Fractional Order and Integer Order Controller Performances

Results show that the fractional order controller, with order of 0.27 and gain $K = 1$, gives better performance than integer order controller. Simulation results comparing the X positions of the three agents are presented in Fig. 6.3(a), Fig. 6.3(b), and Fig. 6.3(c); and Y positions in Fig. 6.4(a), Fig. 6.4(b), and Fig. 6.4(c).

Simulation results also showed that the fractional controller performed better than the integer order controller when a delay was introduced in feedback loop. The fractional controller remained stable while integer order control caused instability. This can be seen in Fig. 6.5(a), Fig. 6.5(b), and Fig. 6.5(c) for X positions; and in Fig. 6.6(a), Fig. 6.6(b), and Fig. 6.6(c) for Y positions.

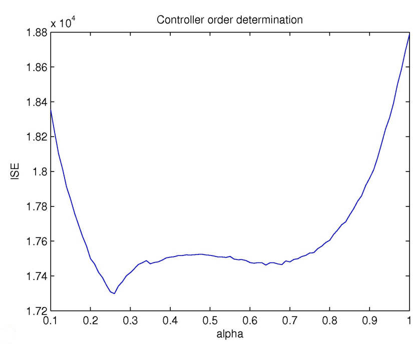


(a) Variation of best gain for X position with fractional order α.

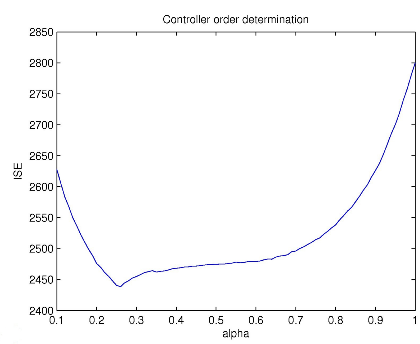


(b) Variation of best gain for Y position with fractional order α.

Fig. 6.1: Best gain variation with fractional order α.

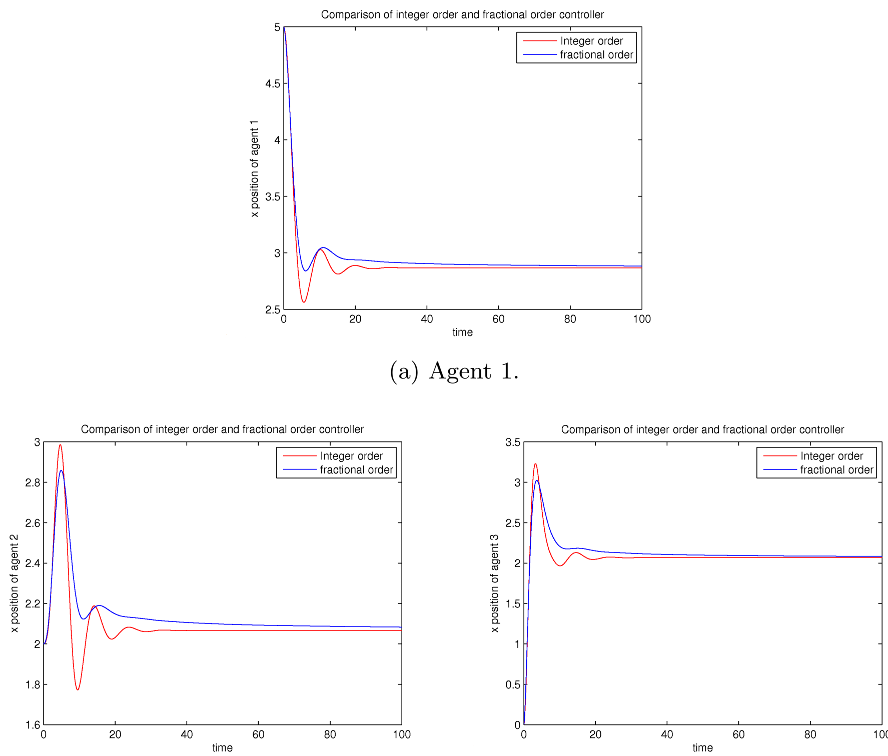


(a) Minimization of ISE for X position.



(b) Minimization of ISE for Y position.

Fig. 6.2: ISE minimizations.

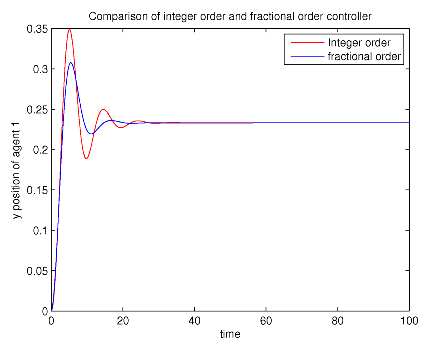


(a) Agent 1.

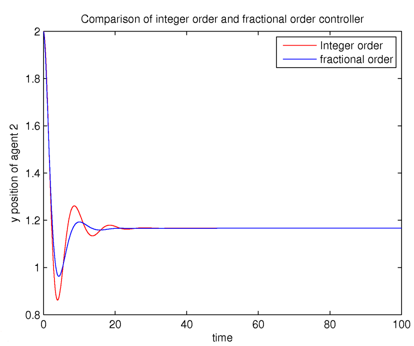
(b) Agent 2.

(c) Agent 3.

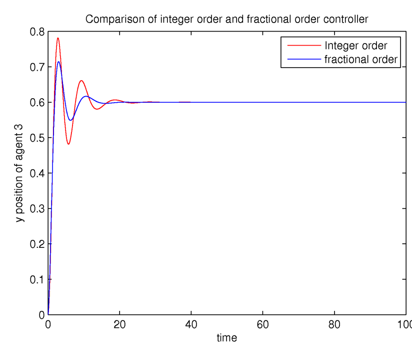
Fig. 6.3: X positions of the three agents over time.



(a) Agent 1.

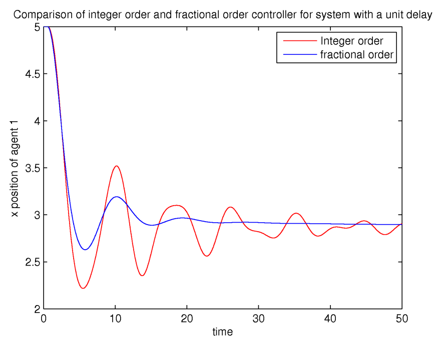


(b) Agent 2.

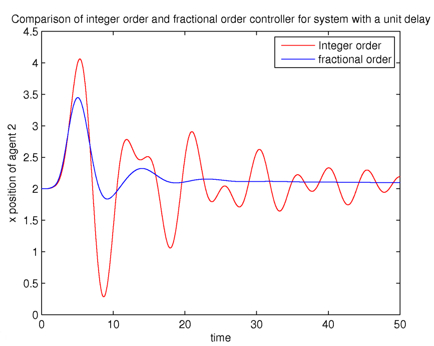


(c) Agent 3.

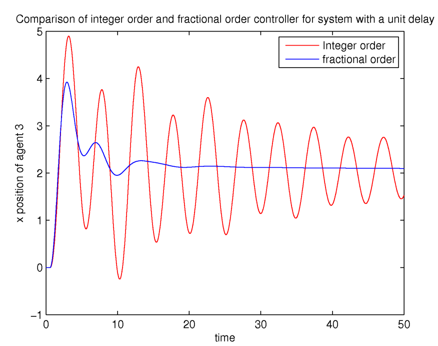
Fig. 6.4: Y positions of the three agents over time.



(a) Agent 1.

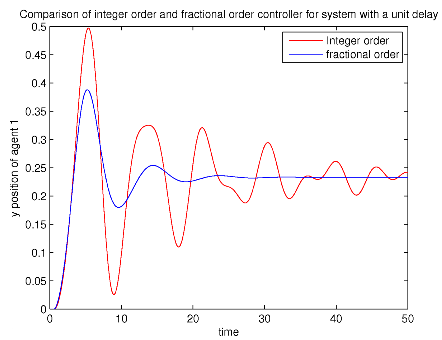


(b) Agent 2.

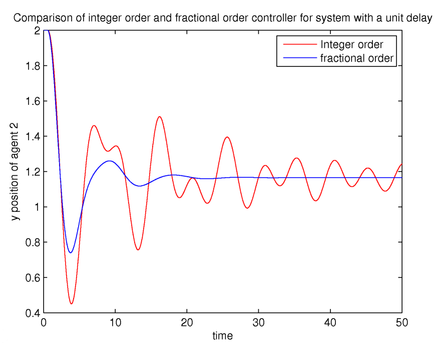


(c) Agent 3.

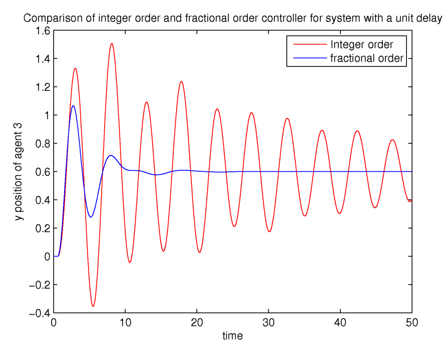
Fig. 6.5: X positions of the three agents over time for system with a delay.



(a) Agent 1.



(b) Agent 2.



(c) Agent 3.

Fig. 6.6: Y positions of the three agents over time for system with a delay.

Chapter 7

String Stability of a Platoon and Effect of Communication Delays

7.1 String Stability

String stability in leader-follower platoons has been a topic of great concern. Intuitively, string stability implies uniform boundedness of all states of an interconnected system at all times if the initial states of the interconnected system are uniformly bounded, as defined by Swaroop and Hedrick [147]. Spacing errors should not amplify downstream from one vehicle to another of the platoon. String stability has proved to be an important tool in analyzing the stability of platoons of vehicles. Shladover [148] pointed out the need for lead vehicle information to obtain string stability with a linear static controller for spacing control. Without leader information, string stability is lost. Tanner et al. [149] analyzed a leader to follower stability, to address issues related to safety and performance due to error propagation in a platoon. The works of Peppard [150] already introduced the idea of string stability in connection to moving cell systems. Peppard defined string stability as the "ability of the vehicle string to attenuate disturbances as they propagate down the string." Conditions for string stability were also provided in the works of Peppard [150], and Shiekholeslam and Desoer [151], in terms of the norm magnitude ($|G(j\omega) < 1|$) and the impulse response ($g(t) > 0$) of the linear operator $G(s)$, where $G(s)$ maps the deviation in the assigned distances between vehicle i and $i-1$.

String Stability is further studied in the works of Swaroop [152], wherein he introduced mathematical definitions for: *string stability, asymptotical string stability, and l_p string stability*. Analysis of the type of information and inter-vehicle spacing strategy that should be employed to achieve string stability has been debated by many authors like Swaroop, and Yanakiev and Kanellakopoulos [152, 153]. In the works of Swaroop, and Yanakiev and Kanellakopoulos [152,153], it was concluded that it was impossible to achieve string stability under autonomous operation when the desired inter-vehicle spacing is constant.

Carlos and Brogliato [154] defined string stability as given by the relation in Eq. (7.1),

$$e_j(s) = \prod_{l=1}^{j-1} G_1(s) \cdot e_1(s) = G(s) \cdot e_1(s), \forall j = 2, 3.....n, \tag{7.1}$$

that gives the transfer function of the backward error propagation, where $G_i(\cdot) : e_i \rightarrow e_{i+1}$. From this relation, we obtain Eq. (7.2),

$$\| e_i \|_\infty \leq \| g * e_1 \|_\infty \leq \| g \|_1 \| e_1 \|_\infty, \tag{7.2}$$

where $g(t)$ is the inverse laplace transform of $G(s)$. A necessary and sufficient condition for error attenuation is given in Eq. (7.3),

$$\| g \|_1 \leq 1. \tag{7.3}$$

Also, if $g(t)$ is positive, then above condition equals Eq. (7.4),

$$\| G \|_\infty = max_\omega |G(j\omega)| \leq 1, g(t) \geq 0. \tag{7.4}$$

If $g(t)$ is not positive, then $\| G \|_\infty \leq 1$ only gives L_2 stability, because of Eq. (7.5),

$$\| e_i \|_2 \leq \| G \|_\infty \| e_1 \|_2 \,. \tag{7.5}$$

These conditions have already been presented in the works of Sheikholeslam and Desoer [151].

For details on linear control strategies based on whether the system is string unstable, l_2 string stable or string stable, refer to the works of Carlos and Brogliato [154]. String stability without communication between the vehicles has been proved by Khatir and Davision [155].

Using nonidentical controllers for each identical vehicle, string stability can be obtained with complete decentralized control, even as the platoon size increases.

7.2 Effect on Systems with Communication Delays

When designing longitudinal controllers for vehicle platoons, it is important to take into consideration, the delays introduced by communication channels in transmitting information between vehicles. Packet drops leading to information loss greatly affects stability. Unreliability of communication channels, limitation on the data transfer rates and random power fluctuations as a signal travels through these links, gives rise to the need to design controllers that can tolerate small system delays without compromising string stability.

Liu et al. [137] developed a sliding mode longitudinal controller to counteract this problem of delays. The spacing error is defined in Eq. (7.6),

$$\epsilon_i(t) = x_i(t) - x_{i-1}(t) + L_i, \tag{7.6}$$

where x_i denotes the abscissa of the rear bumper of the i^{th} vehicle and L_i is the allotted slot to i^{th} vehicle, (i.e., the desired spacing between vehicle i and $i-1$ from rear bumper to rear bumper). ϵ_i measures the deviation in the assigned distance between vehicle i and $i-1$.

Considering the feedback information contains relative position, velocity, and acceleration of both the lead vehicle and preceding vehicles, define Eq. (7.7),

$$S_i = \dot{\epsilon}_i + q_1\epsilon_i + q_3(v_i - v_l) + q_4(x_i - x_l + \sum_{j=2}^{i} L_j), \tag{7.7}$$

where q_1, q_3, q_4 are design parameters. S_i is a function of ϵ_i. It is desired that S_i approaches zero that ϵ_i approaches zero. By setting $\dot{S}_i$ as in Eq. (7.8),

$$\dot{S}_i = -\lambda S_i, \tag{7.8}$$

for some $\lambda > 0$; the control law is given as in Eq. (7.9),

$$\begin{aligned} u_{i_d} &= \frac{1}{1+q_3}[\ddot{x}_{i-1} + q_3\ddot{x}_l - (q_1+\lambda)\dot{\epsilon}_i - q_1\lambda\epsilon_i \\ &\quad -(q_4+\lambda q_3)(v_i - v_l) - \lambda q_4(x_i - x_l + \sum_{j=2}^{i} L_j)]. \end{aligned} \tag{7.9}$$

The actuator lag and signal processing delay is modeled as a first order filter.

$$\tau\dot{u_i} + u_i = u_{i_d}, \tag{7.10}$$

where τ is the "time constant," taken here as 0.05. Differentiating both sides of Eq. (7.6), we get Eq. (7.11) and Eq. (7.12),

$$\dot{\epsilon_i(t)} = \dot{x_i}(t) - \dot{x}_{i-1}(t) = v_i(t) - v_{i-1}(t), \tag{7.11}$$

$$\ddot{\epsilon_i}(t) = \ddot{x_i}(t) - \ddot{x_{i-1}}(t) = a_i(t) - a_{i-1}(t). \tag{7.12}$$

The i^{th} vehicle dynamics is given as in Eq. (7.13),

$$\dot{v_i} = u_i. \tag{7.13}$$

Substituting Eq. (7.6), Eq. (7.11), Eq. (7.12), and Eq. (7.13) into Eq. (7.10) gives Eq. (7.14),

$$\tau\frac{d^3\epsilon_i}{dt} + \ddot{\epsilon_i} = u_{i_d} - u_{i-1_d}. \tag{7.14}$$

The time delays in both the preceding and lead vehicle information are defined as

- $\tau_{dp}^{(i)}$ is the timing delay of the preceding vehicle information seen by vehicle i;

- $\tau_{dl}^{(i)}$ is the timing delay of the lead vehicle information seen by vehicle i.

Substituting Eq. (7.9) into Eq. (7.14) and taking Laplace transform to get transfer function yields Eq. (7.15),

$$\begin{aligned} H_{11}E_i(s) &= \frac{1}{1+q_3}[G_1E_{i-1}(s) + G_2A_l(s) \\ &\quad +G_3A_{i-1}(s) - G_4A_{i-2}(s)], \end{aligned} \tag{7.15}$$

where

$$H_{11} = \tau s^3 + s^2 + (\lambda + \frac{q_1+q_4}{1+q_3})s + \frac{\lambda(q_1+q_4)}{1+q_3}, \tag{7.16}$$

$$G_1 = \lambda q_1, \tag{7.17}$$

$$G_2 = \frac{1}{s^2}(e^{-\tau_{dl}^{i}s} - e_{dl}^{-\tau i-1}s)(q_3s^2 + (q_4 + \lambda q_3)s + \lambda q_4), \tag{7.18}$$

$$G_3 = \frac{e^{-\tau_{dp}^{i}}}{s}(s + (\lambda + q_1)), \tag{7.19}$$

$$G_4 = \frac{e^{-\tau_{dp}^{i-1}}}{s}(s + (\lambda + q_1)). \tag{7.20}$$

For detailed discussion to distinguish the effects of communication delays in lead and preceding vehicle information, see the works of Liu et al. [137]. Currently, there is no controller design that takes these communication delays into account and there is a need to design controllers that adapt to the communication delays.

Chapter 8

Conclusion and Future Work

In this thesis, the concept of vehicle platooning is introduced and a complete, exhaustive literature review of the subject is presented. This thesis reviews all work done on vehicle platooning which can be briefly categorized into the following subtopics:

- Inter-vehicle communication methodologies,
- Collision avoidance and obstacle detection methodologies,
- Design of lateral and longitudinal control systems for platooning,
- String stability of platoon,
- Effect of communications delays on stability.

To show a demonstration of platooning, two research platforms were used. The first one was the Masnet platform. Due to hardware and software issues, this research platform was replaced with the new platform, LEGO Mindstorm NXT 2.0. The Legos were programmed in both LabVIEW and Simulink to demonstrate the vehicle platooning scenario. Vehicle platooning, complete with IVC was achieved on the Lego (programmed in LabVIEW). IVC is yet to be established between the Legos in Simulink. Furthermore, simulation results to show different control strategies for vehicle platooning are also presented in this thesis.

This thesis introduces vehicle platooning and is just the beginning to many possibilities. Future work needs to be done on Simulink to establish inter-vehicular communications between the legos. Making the controller more robust to sensor noise and jitter will be a key consideration for future work. Implementing more complicated controllers to achieve better performance is also needed. The biggest challenge is to implement a fractional order controller on the Legos to achieve platooning. This type of work is completely new and novel and has not been researched in literature at all.

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Appendices

Appendix A

MASnet Platform List of Softwares

A.1 Cygwin

Cygwin is a collection of tools which provide a Linux look and feel environment for a Windows based machine. It is a DLL which acts as a Linux API layer providing substantial linux API functionality.

A.2 TinyOS

It is an open source,component-based operating system and platform,targeting wireless sensor networks. It is an embedded operating system, written in NesC programming language.

A.3 NesC

It is a component-based event driven programming language, used for building applications for the TinyOS platform.

A.4 MicaZ

It is 2.4 GHz programming board, manufactured by Crossbow, to enable low power, wireless sensor networks.

A.5 Crossbow

This is a California based company that manufactures MicaZ motes and also makes a software design platform for its hardware, called Moteworks.

A.6 Moteworks

Crossbow's open integrated, standards based platform for the development of wireless sensor networks OEM devices and systems.

Appendix B

Upgrading the System to Windows 7 Based Machine

The MASnet platform was used for developing applications right from the year 2003 to date, and was using a Windows XP based machine. This was upgraded to make the system functional on Windows7. The following work is needed to in case another upgrade is to be made.

- Reinstallation of Moteworks, Cygwin and TinyOS

  If using Moteworks, a reinstallation of all the related softwares is needed to avoid compilation errors that arise due to version mismatch. One of the issue that arises in this process reads as follows:

  "C:\Crossbow\cygwin\bin\bash.exe" has stopped working, "\usr\bin\bash\fork:bad file description"

  Note: Cygwin has Setup.exe version 2.510.2.2 Installed with Moteworks. Cygwin downloaded off the internet has a Setup.exe version of 2.738.

  Attempted Fix: Run Setup.exe v2.738 to reinstall all essential cygwin packages. Replace Setup.exe v2.510.2.2 with v2.738 in "C:\Crossbow\cygwin-installationfiles."

  Hence, Moteworks has old versions of programs and it might be necessary to find new versions and install them separately so they replace the older versions. A list of free software packages that are installed with Moteworks but should be able to be updated with newer versions are:

  [1] nesC Compiler,

  [2] Cygwin,

  [3] Programmers Notepad,

[4] TinyOS.

- Post install script errors for Cygwin

  Check the “\var\log\setup.log.full”. Moteworks should have installed the following:

  [1] Cygwin,

  [2] Programmer’s Notepad 2.0,

  [3] Graphviz 2.6,

  [4] XSniffer,

  [5] MoteConfig 2.0 and OTAP,

  [6] Microsoft .Net framework,

  [7] nesC 1.2 compiler,

  [8] GCC compiler.

- Cygwin Experience Files

  These files will never be overwritten nor automatically updated.

  [1] ‘./.bashrc’,Location: “/home/MASNET//.bash_ profile”

  [2] ‘./.bash_profile’,Location:“/home/MASNET//.inputrc”

  [3] ‘./.profile’,Location:“/home/MASNET//.profile”

If an older version of Cygwin is necessary, install Cygwin 1.5 as opposed to the newest Cygwin 1.7.

B.1 Cygwin Experience Files

- ‘/.bash_profile’ - Personal Initialization file. It runs only for bash login shells and is used to set environment variables, create aliases for shell commands and set default permissions for newly created files.

- ‘ /.bashrc’- Individual pre interactive shell startup file. Similar to “.bash_profile” and runs for every new bash shell. Not automatically called for login shells.

- All windows environment variables are imported when Cygwin starts. Some settings need to be in effect prior to launching the initial Cygwin session. These settings for Cygwin are placed in an initial file called “Cygwin.bat,” which should be set or modified in the Windows environment.

- ‘/.profile’ contains bash commands. It runs when bash is started as login shell. Useful place to define and export environment variables and bash functions that will be used by bash and the programs invoked by bash. It is recommended to add “:,” at the end of the path to search for current working directory.

- ‘/.inputrc’- it controls how programs using the read line library behave. It is loaded automatically.

If Moteworks does not work properly, then a manual installation of TinyOS using Cygwin on windows is an officially supported method of installation by the TinyOS open source community. In this case, completely remove Moteworks and focus solely on the installation instructions provided by the TinyOS community.

Fix to some more errors are given below.

When ‘.bashrc’ or ‘.bash_profile’ is read, messages such as “\r” command not found, may be obtained.

Fix: When you get rid of empty lines, the message disappears. The text file comes in two formats, DOS or UNIX. In DOS, a new line is represented with two characters. Other errors include CR (carriage return) and LF (line feed). In UNIX, a new line is represented by only one character, LF. When bashrc is read, bash thinks the extra character is the name of a command. Simple fix is to remove that character.

B.2 Cygwin Issues

If the error like “ls:unkown option” occurs, a simple fix is to add “C:\cygwin\bin” and “C:\cygwin\usr\sbin” to the path. The procedure is as follows.
Create a new environment variable “Env CYGWIN-HOME =”, add “$CYGWIN.HOME\bin” and “$CYGWIN.HOME\sbin” If on compilation, the error “OSROOT/support/make/Makerules:no such file or directory” is obtained, fix it by changing the environment variables MAKEULES as “$(TOSROOT)/support/make/Moteworks.”